1 **A Pyroclastic Flow Deposit on Venus**

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7

8 **Abstract**

9 Explosive volcanism on Venus is severely inhibited by its high atmospheric pressure and lack of
10 water. This paper shows that a deposit located near 16°S, 144°E, here referred to as Scathach Fluctus,
11 displays a number of morphological characteristics consistent with a pyroclastic flow deposit. These
12 characteristics, particularly its lack of channelisation and evidence for momentum rather than cooling
13 limited flow length, contrast with fissure-fed lava flow deposits. The total erupted volume is estimated
14 to have been between 225 km³ and 875 km³ but this may have been emplaced in more than one event.
15 Interaction between Scathach Fluctus and a small volcanic cone constrain the flow velocity to
16 48 m s⁻¹ and plausible volatile concentrations to at least 1.8 wt% H₂O, 4.3 wt% CO₂ or 6.1 wt% SO₂,
17 the latter two implying magma sourced directly from the mantle. The deposit has radar characteristics,
18 particularly an exponential backscatter function, that are similar to those of nearly half the planetary
19 surface, implying that pyroclastic deposits may be much more common on Venus than has been
20 recognised to date, and suggesting both a relatively volatile-rich mantle and a volcanic source for
21 atmospheric SO₂.

22

23 Volcanic processes dominate the surface of Venus, with features including plains-
24 forming flood lavas, large shield volcanoes, calderas, clusters of small volcanoes, and

25 sinuous lava channels (Head et al., 1992). There is a notable absence of pyroclastic activity.
26 This must in part be a result of the inhibiting effect of high atmospheric pressure (Head and
27 Wilson, 1986), but it is also consistent with a lack of volatiles in volcanic magmas and
28 therefore in the interior of Venus. Many terrestrial volcanoes lie within a compositional
29 spectrum between primary, relatively volatile-poor effusive basalts and evolved, relatively
30 volatile-rich, often explosive, andesites and other silicic magmas. The major volatile
31 component is usually water, which may be sourced directly from fertile mantle in basalts
32 (Green, 1973) or enriched in evolved magmas through dehydration of subducted crust at
33 convergent plate margins. Magellan imagery and Venera lander data (Surkov and Barsukov,
34 1985) imply that the majority of Venus' volcanics are basaltic in composition, although there
35 is some evidence for compositions richer in silica (Fink et al., 1993, Bridges, 1997, Shellnutt,
36 2013), sulphate (Kargel et al., 1994) or carbonate (Williams-Jones et al., 1998, Komatsu et
37 al., 2001), the latter of which implies silica-poor evolved magmas (Hess and Head, 1990) that
38 erupt effusive low viscosity flows. The interior is extremely dry with respect to water, with
39 perhaps only 50 ppm water in basaltic magmas (Grinspoon, 1993). The limited and equivocal
40 observational evidence for explosive eruptions on Venus (Campbell, 1994, Guest et al., 1992)
41 is consistent with this inference of a dry interior. The abundance of the other major volatiles,
42 CO₂ and SO₂, is unknown but assumed to be Earthlike (Bullock and Grinspoon, 2001). This
43 paper presents evidence for a volatile-rich pyroclastic flow deposit located near Diana
44 Chasma at 16°S, 145°E. We name this deposit Scathach Fluctus, after a Celtic destroyer
45 goddess meaning 'the shadowy one'.

46 **1. Identification**

47 Scathach Fluctus is identified as a semi-circular doughnut-shaped deposit located on
48 the boundary between plains north of Diana Chasma and fractured terrain west of Ceres
49 Corona (Figure 1). The perspective view in Figure 1a shows that the deposit is relatively flat

50 and not associated with a volcanic rise. The false colour images in Figures 1 (b) to (d) and
51 Figure 2 use data from Cycle 1 (left-looking), Cycle 2 (right-looking) and passive emissivity
52 combined to enhance the impression of relief in the grey scale image, overlain with colour-
53 coded derived asperity height (roughness) at the scale-length of the Magellan radar
54 wavelength (126 mm). Asperity is defined as the surface roughness, h , on the scale of the
55 radar wavelength, and is calculated using the Small Perturbation Model (Chen and Fung,
56 1988) for Cycle 1 data at the appropriate incidence angle. Since Cycle 1 incidence angle
57 varies with latitude, the asperity values derived are not strictly comparable between different
58 images; in practice, however, the differences are small at low latitudes, and for data in the
59 latitude of the images shown, asperity can range from less than 10 mm (very smooth) to
60 about 40 mm (very rough). The surface may of course be rougher than this but not on the
61 length scale of the radar signal (126 mm); i.e., the surface may be modulated by larger
62 amplitude undulations but they will be on a longer length scale. Thus asperity is not sensitive
63 to larger-scale features, such as the ~100 mm undulations across pahoehoe-type flow lobes,
64 but is sensitive to the roughness of individual lobe surfaces.

65 The deposit itself (Figure 1b) is superficially similar to, and intermediate in size
66 between, an anemone (Head et al., 1992), an example of which is shown in Figure 1c, and the
67 lobate flows shown in Figure 1d, both of which appear to originate at fissures. At first sight
68 Scathach Fluctus also appears to originate at a fissure (the yellow/red linear feature oriented
69 NE to SW across the centre of Figure 1b, immediately to the right of the b.i arrowhead) but
70 this feature cuts across part of the deposit and a number of other features and may therefore
71 be a more recent tectonic structure. All that can be stated with confidence is that the source
72 lies somewhere in the region of the fractured but otherwise smooth surfaces in the vicinity of
73 15.8°S, 145.3°E. Although most apparent on the plains west of this source region, the deposit
74 is also discernable across fractured terrain to the south, but with a clear right-angled gap in

75 the SW which, together with other smaller gaps and irregularities, may indicate multiple
76 emplacement events.

77 Figure 2 shows two sections of the western deposit, where it lies on the plains, printed
78 at the highest resolution of the Magellan data (which at this latitude is about 110 m in both
79 range and azimuth), as well as part of the anemone featured in Figure 1. The smoothest areas
80 of the images have an asperity of less than 10 mm; the roughest parts of the flow surface have
81 an asperity of about 30 mm and in places up to 40 mm.

82 The smoothest areas to the east of the deposit (Figure 2a.i), nearer the source region,
83 are similar in roughness to the plains and may simply be a smoother part of the deposit,
84 buried by fine grained sediment (which need only be a few centimetres thick), or may be an
85 area altogether free from flow material. The anemone likewise has a smooth region between
86 the source fissure (Figure 2b.i) and the first appearance of rough surfaces away from the vent
87 (Figure 2b.ii). However, at the anemone, some slight roughness variations can be traced
88 directly from the fissure to the area of channel-like flows (Figure 2b.iii). This morphological
89 arrangement is that expected for a fissure-fed lava eruption. Initially, lava spreads from the
90 fissure as a near-uniform sheet flow; as lava gets further from the fissure more of it cools and
91 it acquires an increasing effective yield strength. Topography undulations cause thickness
92 variations in the flow, so that the increasing yield strength is not the same everywhere, being
93 greatest where the flow is thinnest and it is here that incipient stationary levees start to form.
94 These have a finite thickness initially just equal to the current thickness of the sheet flow but
95 with further cooling the yield strengths increase and the levee-like structures get thicker. This
96 process forces the hot lava flowing between any two levees to get deeper, to keep up with the
97 thickening levees, and so flow faster; but this is prevented by the constant volume flux per
98 unit length along strike of the fissure. The only option is for the flowing lava to form
99 narrower streams and so the levee-like zones split, each half of each one forming the levee on

one side of each of a series of now discrete, thicker, faster, narrower channelized flow units growing alongside one another. As expected at a cooling-controlled terminus of a lava flow (Borgia et al., 1983; Bruno and Taylor, 1995; Blake and Bruno, 2000), the anemone flow units terminate in lobate margins (b.iv) that have an asperity similar to that of the channel levees along the flow margins. The distances from the inferred vent region to the points where flows first diverge is 4.5 to 5.5 km, and the distance from the vent to the flow termini is 19 to 23 km. Using data on cooling-limited flows on Mt. Etna (Pinkerton and Wilson, 1994) modified by later observations on Hawaiian flows (Soule et al., 2004), these distances are consistent with volume fluxes feeding individual flow lobes within a factor of 3 of 300 m³ s⁻¹.

Within Scathach Fluctus, there is some evidence for rougher material towards the east in the smooth area but there is no evidence for channelization in the rougher part of the deposit, and the morphology of this rougher part of the deposit is very different from the channelized area of the anemone. Rather than being channelized, the main part of the deposit appears to undulate in thickness from north to south (Figure 2a.ii), with these undulations forming more-or-less linear deposits from the east to the western margin. The deposit appears to thin towards the western margin but other than a regional slope there is no measurable change in elevation.

The two deposits contrast particularly in their interaction with local graben. The flows from the anemone deviate into a narrow graben (Figure 2b.v) as they cross it. The flows also enter a graben towards their terminus (Figure 2b.vi); the flow widens and just fills the graben but does not flow along it, again indicative of a cooling-limited deposit.

By contrast, the margins of Scathach Fluctus do not deviate in flow direction across graben (Figure 2c.i shows the clearest example but the same can be seen in Figure 2a), indicating a high-momentum flow. The graben often remain partially visible through the

flows, which may indicate that the graben are more recent, but in at least some instances the flows interact with graben. The deposit is often rougher within the graben (Figures 2a.iii and c.i), having an asperity up to 50% greater than average. These features indicate that the flows often only partially fill any graben that are crossed and perhaps do so preferentially with coarser material. The implications are that the flows may be stratified (Fisher and Heiken, 1982, Fujii and Nakada, 1999), with a coarser base, and that as the flows cross a graben, the lower, coarser, part falls under gravity and deposits material into the graben floor on a parabolic trajectory, while the upper, finer, part continues across the graben without any noticeable change, indicative for pyroclastic flows where portions of the ground-hugging avalanche is hindered from travelling farther. At obstacles, such as fault scarps, the basal avalanche can be deflected while the overriding dilute gas-fine particle cloud does not change its path. These features are most clearly visible in the very large graben at the eastern margin of the deposit (Figure 2a.iv), in which flow material is visible piled up against the western wall of the graben. At their margins, the flows often terminate within graben, which they apparently flow along, indicating that in these places no part of the flow has sufficient momentum to cross the graben.

These characteristics are interpreted as representing a low density, high velocity pyroclastic flow deposit (Wright et al., 1980). It appears that the flow first slowed sufficiently to deposit material as it crossed the easternmost wide graben, after which material was continuously deposited until momentum and forward velocity was lost at the terminus of the deposit. The largest fragments were likely deposited first and hence the thickest and roughest part of the flow is towards the east, and it has relatively thin and smooth margins. The long, near-linear undulations represent random differences in flow particle concentration with distance from the source, stretched out east-west by the velocity of the flow.

2. Characterisation

Scathach Fluctus is fortuitously located in an area of Venus covered by all three Magellan imaging cycles (left, right and stereo) as well as the full range of ancillary data derived from the altimeter. These have been used to enhance the image data with shaded relief and asperity information, but in addition these data can be used to provide parallax measurements and some constraints on the physical nature of the deposit and the surrounding terrain.

The patchy appearance of the deposit and the presence of the partly buried graben imply a thin deposit. Parallax measurements can only determine the height of the surface of the deposit and not its thickness (for a full description on how parallax measurements are obtained, see Leberl et al. (1992)), but where the flow crosses and completely buries a graben (e.g., in the lower part of Figure 2a), an estimate of its local thickness can be obtained from estimates of the depth of the graben adjacent to the flow. Although the majority of the graben are too narrow for reliable parallax measurements, their depths may be estimated from the width of their flanks, using radar incidence angle to obtain a minimum depth estimate and probable slope angles to obtain a maximum estimate (McGill and Campbell, 2006), assuming axially symmetric slopes. These indicate that the graben are commonly between 100 and 200 m deep, but locally may be up to twice this depth. Therefore the thickest parts of the deposit in the graben may be up to 200 m thick. Away from the graben the flow will be thinner; a reasonable estimate may be 50 m. Taking this estimate and only the area of the rough part of the flows on the plains, 4500 km², provides a minimum estimate of the erupted volume: 225 km³, about twice that of the 1815 Tambora eruption (Sigurdsson and Carey, 1989, Self et al., 2004), although as noted earlier this Venus deposit may not have been produced by a single event. A further 3500 km² can be traced across the fractured terrain in the south. In the west the deposit has a distinct emissivity (dotted outline in Figure 3a) relative to surrounding features; although it is less distinctive in the east, the assumption of

radial symmetry provides a maximum area estimate of 17 500 km². Assuming 50 m as an upper estimate for its average thickness yields a volume of 875 km³, approaching the volume of the Taupo, Yellowstone and Toba caldera-forming events (Mason et al., 2004) but note again that Scathach Fluctus may represent more than one event.

An estimate of the flow velocity may be obtained from analysis of the interaction between the flow and a small volcanic cone (Figure 2c). The deposit appears to be piled up on the eastern flank of the cone and to have left a hydrodynamic (tear-drop shaped) wake to the west of it. Assuming the vent of this 7 km diameter volcanic cone is at its centre, the height reached by the deposit on the eastern flank can be determined by parallax. Accounting for the 0.9° regional slope, the flow deposits cover the lower 130 m of the eastern flank of the 540 m high cone. Assuming that this equates to the ‘just stop’ obstacle height, $H = v^2/2g$, obtained by equating the kinetic energy of the approaching flow to the potential energy required to rise onto the obstacle, then the flow velocity was 48 m s⁻¹ at this location, approximately 40 km from the centre of the emissivity feature. This is low in comparison to velocities inferred from similar-sized terrestrial events, e.g. 250 m s⁻¹ at a distance of ~13 km from the vent for the ~186 A.D. Taupo ignimbrite (Wilson, 1985). The low speed is directly attributable to the high atmospheric pressure on Venus, which necessitates a higher volatile concentration to generate an explosive eruption. Via the link between magma volatile content and ejecta velocity in explosive eruptions (Wilson, 1980), the velocity tightly constrains the concentration of the three plausible volatiles, H₂O, CO₂ and SO₂ to 1.8, 4.3 and 6.1 wt% respectively, calculated using the same relationships as those in Head and Wilson (1986) and independently, i.e., not for a mixture of these gases. These are high in comparison to terrestrial magma values and both the latter are more than double the saturation level (Leone and Wilson, 2001) in the crust, implying that explosive activity from a long-lived magma chamber in the crust must be primarily water-rich. Since crustal or subducted water is

unlikely under Venusian conditions, its source is most likely primordial water in the mantle, concentrated through fractionation. Although crustal sources of carbonate or sulphate, are possible (Kargel et al., 1994), which might explosively interact with ascending magma, CO₂ or SO₂-rich magmas may imply a direct mantle source (Green and Gueguen, 1974) and a kimberlite-type explosive eruption event (Wilson and Head, 2007).

3. Significance

Is Scathach Fluctus unique, or are pyroclastic flow deposits common on Venus but unrecognised? The distinctive emissivity of the deposit is only noticeable because the adjacent plains have an unusually low emissivity of 0.751 ± 0.005 , significantly lower than is normal for Venus. Together with a Fresnel reflectivity of 0.224 ± 0.007 and a backscatter coefficient of -13.9 ± 2.9 dB, the unusual properties of these plains are consistent with high dielectric bedrock mantled by fine-grained granular sediment. Adopting the same procedure and assumptions as Campbell et al. (1992), we calculate a sediment depth of 0.46 m and a rock substrate dielectric constant of 11.5, higher than expected for a normal basalt (~ 7.5) and most likely a result of a high-dielectric or ferroelectric phase. Approximately 2 wt% TiO₂ in the form of the high-dielectric phase perovskite, CaTiO₃, is sufficient to account for the inferred dielectric constant. This is only slightly higher than the 1.6 wt% measured by Venera 13 (Surkov and Barsukov, 1985) and the 1.19 to 1.77 wt% range of mid-ocean ridge basalts (Basaltic Volcanism Study Project, 1981). Similar attenuations and inferred sediment depths are obtained from the central area of Scathach Fluctus. While the granular sediment may plausibly have originated from the nearby impact crater Halle, it is tempting to suggest an air fall origin for the material from the turbulent upper part of the pyroclastic flow (as illustrated in, for instance, Fisher and Heiken (1982) and Fujii and Nakada (1999)).

The emissivity of the visible (rougher) parts of Scathach Fluctus is 0.847 ± 0.002 , similar to that of average Venus surface, and corresponds to a density close to 2000 kg m⁻³

based on relationships in Campbell (1994) and Rust et al. (1999), which is towards the upper end of the range of pyroclastic flow deposit densities (1240 to 2360 kg m⁻³, Lepetit et al. (2009)). It implies that the flow must be welded with little or no remaining porosity, giving it the radar characteristics of a solid surface.

The surface scattering function (Figure 3b), recorded in the Magellan global vector data record (GVDR), may be used to characterise the metre scale nature of the surface (see (Tyler et al., 1992) for further details on the processing and data products). The plains adjacent to Scathach Fluctus are characterised best by a Gaussian scattering function, implying an undulating surface, whereas the fractured terrain is characterised very well by all three (Gaussian, Hagfors and Exponential) scattering functions, indicating a spectrum of surface types. The main area of Scathach Fluctus is characterised best by an exponential function, implying very flat surfaces, which may be tilted, at the metre scale, as might be expected for a pyroclastic deposit, however, this observation is by no means definitive. More than half the surface of Venus is characterised by an exponential scattering function (Tyler et al., 1992), mainly in the plains. Thus it is possible that a large fraction of the Venus surface may have originated as pyroclastic flow deposits; however, identifying such deposits convincingly may prove extremely difficult, particularly where flow boundaries are no longer visible.

Observations should focus on the identification of high momentum features and be supported by analyses of emissivity and reflectivity data. Even then, it may be impossible to properly distinguish between lava flows and pyroclastic flow deposits that are weathered or otherwise altered. Unwelded air fall deposits were tentatively identified on the southern flank of Tepev Mons, located at 15°S, 45°E, on the basis of their radar attenuation (Campbell, 1994) but Scathach Fluctus is the first welded flow deposit to be identified. If there are significant numbers of other unidentified pyroclastic deposits then the interior of Venus may be

relatively volatile-rich, with significant implications for interior chemistry (Falloon and Green, 1990) and atmospheric evolution (Marcq et al., 2011, Marcq et al., 2013).

4. Conclusions

A large pyroclastic flow deposit has confidently been identified on Venus on the basis of its flow morphology. Its size indicates a large, or series of large, explosive events, on a scale similar to those of the largest such terrestrial events in historical times, and implies a volatile content much greater than expected. The radar properties of the flow indicate that it is a welded, solid material that may be difficult to distinguish from other materials on the Venus surface. However, its exponential backscatter function implies that perhaps welded pyroclastic flow deposits may be much more common than previously realised, covering up to half the planetary surface, and implying a volatile-rich mantle and a volcanic source for atmospheric SO₂. Unfortunately, because the plains usually lack clear flow boundaries and structures, the features diagnostic of a high momentum flow – linear undulating deposits that lack channel morphology, cross narrow graben without deviation, climb obstacles and show evidence for parabolic flow out from steep drops – may not be identifiable. Scathach Fluctus may, indeed, prove unique.

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Figure Captions

Figure 1

Three volcanic deposits are shown at the same scale to illustrate the similarities and differences between them. The deposits are all located in the equatorial region of Venus close

to eastern Aphrodite Terra (1a). Scathach Fluctus (1b) is intermediate in size between an anemone (1c) and a lobate flow deposit (1d). All three are smoother nearer their presumed source and have rough termini. The anemone has a clearly defined central vent but there is no obvious source for either Scathach Fluctus or the lobate flows. Although very different in scale, both the anemone and lobate flows have curvilinear channel-like morphologies that are absent at Scathach Fluctus.

Figure 2

The highest resolution Magellan imagery reveals the differences in interaction of the Scathach Fluctus (2a, c) and anemone (2b) flows with pre-existing topographic features. In 2a, Scathach Fluctus flows are smooth to the east of a wide graben (with flanks marked A and B). Within the graben the flow appears to be absent from the eastern flank (B) and piled up against the western flank (A), indicative of parabolic trajectory across the graben and implying a flow with considerable forward velocity and momentum. Similarly the flow is piled up on the eastern flank of a small volcano (2c) and bifurcates, leaving a flow-free tail to the west of the volcano. There is some evidence for a thin veneer of pyroclastic flow material on the upper part of the volcano near the vent (2c.iv). This may be material deposited from the upper part of the pyroclastic cloud or material that partially travelled up the edifice leaving a thin veneer at the top whereas elsewhere on the flanks it has been eroded/not preserved or is not detectable. The relatively straight flow lines and lack of channel morphology in these flows contrasts with the non-linear channel-like flows of the anemone, which also appear to be more strongly influenced by topographic features, notably the narrow graben visible as a pale line from B to C.

Figure 3

399 Scathach Fluctus is distinguishable as an almost circular green feature intermediate in
400 emissivity between the high emissivity (~ 0.9) of the densely fractured terrain and the low
401 emissivity (~ 0.7) of the plains. The Global Vector Data Record (GVDR) shows the scattering
402 law that most closely fits the altimeter backscatter data; the plains mainly have a Gaussian
403 distribution indicative of a smooth surface with discrete blocks, while the highlands are
404 closer to a Hagfors distribution indicative of a rough, blocky surface. Parts of Scathach
405 Fluctus are closer to an exponential distribution, indicative of a flat or gently undulating
406 surface.

1 (a) Localities

False colour Magellan SAR image of eastern Aphrodite Terra, in the equatorial region of Venus. The localities referred to in the text, and illustrated in detail below, are indicated along with the names of the principal geographical features in the region.

1 (b) 16s145 Scathach Fluctus

1 (c) 7s199 Anemone

(b), (c) and (d)
Common Scale
and Key

1 (d) 15s140 Lobate Flows

2 (a) 16s145 Scathach Fluctus

2 (b) 7s199 Anemone

2 (c) 16s145 Scathach Fluctus interaction with a volcano

3 (a) Emissivity

3 (b) GVDR best fit to Altimeter Data