



Particulate gravity currents on Venus

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[1] Canali are moderately sinuous channels, typically a few kilometers wide and hundreds of kilometers long, that occur principally on the plains of Venus. Plausible hypotheses for their formation include the following: open channels cut by exotic, low-viscosity lavas; roofed-over basaltic lava channels; or water on a cooler, wetter ancient Venus. Although it is accepted that a fluid cut these channels, none of these hypotheses are entirely satisfactory. It is therefore prudent to investigate other explanations. A particulate gravity current is a rapidly moving, sediment-laden flow that moves downslope as a result of its high density compared to the ambient fluid. This high density is produced by suspension of dense particles in a lower-density fluid. As these flows are largely driven by slope, rather than by momentum, they are potentially capable of traveling great distances, producing extensive channel systems. We apply this process to Venus, exploring its channel-forming potential via mathematical modeling and morphological comparison of submarine channels on Earth to canali on Venus. Results of our modeling show that atmospheric particulate gravity currents are physically and geologically plausible on Venus. The potential of this process to form channels of great length is such that particulate gravity currents can be considered as an alternate explanation for canali genesis.

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1. Introduction

1.1. Particulate Gravity Currents

[2] Gravity currents are fluid flows moving downslope as a result of their high density compared to the ambient fluid (e.g., lava flows downslope because it is denser than the atmosphere). In a particulate gravity current, this high density is produced by suspension of dense particles in a lower-density fluid. Several examples occur naturally on Earth, such as powder-snow avalanches (snow grains suspended in air [Hopfinger, 1983]), pyroclastic surges (volcanic ash suspended in hot gas [Sheridan, 1979]) and submarine turbidity currents (sand and mud suspended in water [Komar, 1979; Shanmugam, 2000]). Note that such currents are largely driven by slope-generated pressure gradients rather than by momentum and are therefore potentially capable of traveling great distances.

[3] In a turbidity current, the volumetric concentration of particles is typically of the order of a few percent (e.g., 4% for the Black Shell turbidite [Dade and Huppert, 1994]). Individual turbidite flows last hours to weeks, with Khrispounoff *et al.* [2003] documenting a single flow in

the Zaire channel lasting 10 days. Turbidity current channels are built by the action of many such flows over time and form as a result of erosion in the upper reaches and, in the lower reaches, by aggradation as sediment is preferentially deposited outside the channels from over-bank flow. This is the main process by which sediment is distributed across the Earth's near-horizontal deep-ocean seafloor. Pirmez and Imran [2003], for example, show that the Amazon channel and the surrounding sediments have been generated by a flow every year or two for the last thirty thousand years. Individual flows are initiated by slope collapse, often as a result of nearby earthquakes (e.g., the Grand Banks slide of 1929 [Piper *et al.*, 1985]). Oversteepened slopes normally result from the build-up of deltas at river mouths but they can result from tectonic processes as occurs in the Niigata-Shin'etsu basin, Japan [Tokano *et al.*, 2005], and in the sediment-starved subduction trench west of Peru (N. Kukowski, personal communication, 2006).

1.2. Application to Venus

[4] The atmospheric density at the surface of Venus is more than 50 times greater than that on Earth and about 6.5% that of water [Seiff, 1983]. As a result, the Venusian atmosphere may be able to support denser particulate gravity currents than the Earth's, perhaps being more akin to submarine turbidity currents. This is not a new hypothesis. In a paper published nearly 40 years ago, Ronca and Green [1970, p. 63] stated the following:

On Venus, the settling velocity is approximately one or two orders of magnitude smaller than on the Earth's surface atmosphere. This implies

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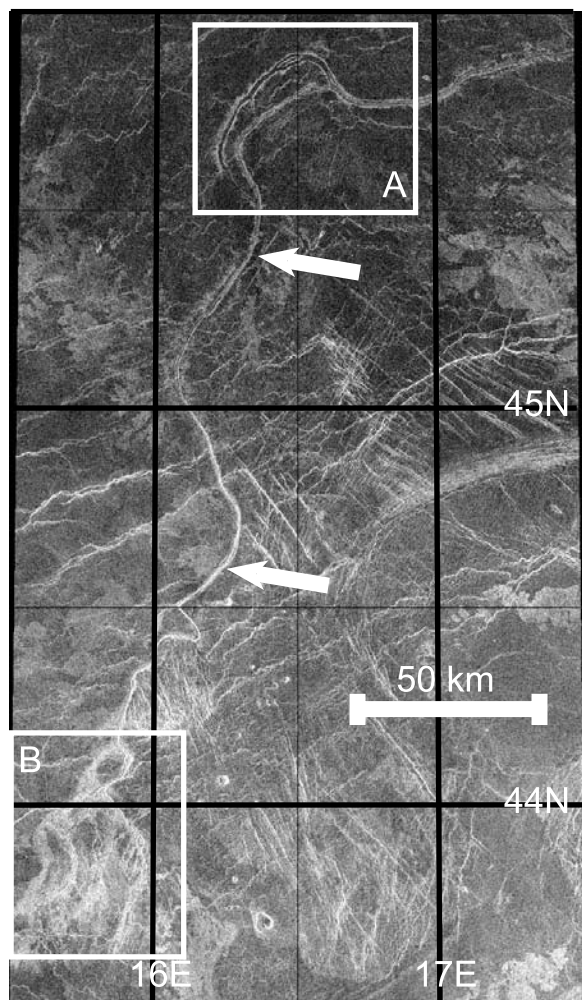


Figure 1. A well-preserved canali-type channel on Venus (arrows). Note the near-constant width and similarity to fluvial- or submarine-channel morphology. Box A indicates possible levées. Box B shows a terminal fan complex. Magellan left-look radar image is courtesy of NASA Planetary Data System Imaging Node, U.S. Geological Survey, Flagstaff, Arizona.

that auto-suspension may be much more common on Venus, provided differences in elevation occur. If mountains exist, it is possible that the downslope movement has carved a system of drainage canyons with accompanying ponded sediments and abyssed plains in a manner similar to turbidite currents in the Earth's oceans.

This may turn out to be a remarkable prescient statement, made decades before the availability of Magellan imagery of the Venusian surface.

[5] Here, we present mathematical modeling results and morphological comparison of Venusian channels to terrestrial submarine flows to demonstrate that particulate gravity flows are physically possible on Venus. To explore the potential channel forming power of this process, we test our model by applying it to the longest subset of Venusian channels, canali.

[6] Canali (Figure 1) are moderate-sinuosity channels crossing the Venusian plains and have widths of a few kilometers and lengths of hundreds to thousands of kilometers [Baker et al., 1992, 1997; Baker and Komatsu, 1994;

Komatsu and Baker, 1996; Komatsu et al., 1993]. A number of authors [Baker et al., 1992; Komatsu et al., 1992; Kargel et al., 1994; Bussey et al., 1995; Williams-Jones et al., 1998; Bray et al., 2007] have suggested that the canali-type channels result from low-viscosity carbonatite or sulfur magmas. An alternative is lava flowing beneath a thermally insulating crust, allowing greater transport distances [Komatsu et al., 1992; Gregg and Greeley, 1993] as occurs on Earth [Ho and Cashman, 1997]. A related alternative is subsurface fluid flow episodically deforming overlying material [Lang and Hansen, 2006]. Finally, Jones and Pickering [2003] suggested that the canali may have been cut by water flowing on a far cooler and wetter ancient Venus. Although it is accepted that these channels were formed by the action of a fluid, a consensus on the formation mechanism is yet to be reached. It is therefore prudent to investigate other explanations. Here, we show that slope-failure-generated particulate gravity currents in the dense atmosphere of Venus are not only a plausible Venusian surface process, but are capable of producing extensive channels. Thus, in this paper, we do not propose that canali were formed in an identical manner to submarine channels since this would require oceans to have existed on Venus in the relatively recent past. Instead, we propose canali formation by particulate gravity currents in the atmosphere of Venus. This explains many features of canali without requiring significantly different conditions to those observed today.

[7] Section 2 demonstrates that the morphology of Venusian canali is more similar to submarine channels on Earth than to volcanically formed sinuous rilles on either Venus or the Moon. Hence lunar rilles are not good analogues for canali-type channels, and a different mechanism must be found for canali formation. Following this, we show that atmospheric particulate gravity currents are physically and geologically plausible on Venus and that this concept therefore deserves to be considered as an alternate explanation for canali genesis.

2. Morphological Properties

2.1. Channel Length

[8] Canali are not generally preserved along their entire length. In most cases neither the channel origin nor its termination are observed on the current surface of Venus. Nevertheless, preserved segments of Venusian canali are frequently hundreds or thousands of kilometers long. Baltis Vallis, the longest known channel in the solar system, has mappable segments totaling around 7000 km in length [Baker et al., 1992, 1997; Komatsu et al., 1993; Bray et al., 2007]. Terrestrial river and submarine channels are the only other channels in the solar system of comparable length. The longest of the submarine channels is the Bengal Submarine Fan, which measures 3000 km in length [Curry and Moore, 1971]. The Cascadia, Indus and Mississippi submarine channels [Clark and Pickering, 1996], along with the Amazon [Pirmez and Imran, 2003] and Zaire [Babonneau et al., 2002] submarine channels, all have lengths in the range 500–2000 km. In comparison, sinuous rilles on the Moon and Venus are relatively short with lengths of typically 100–500 km.

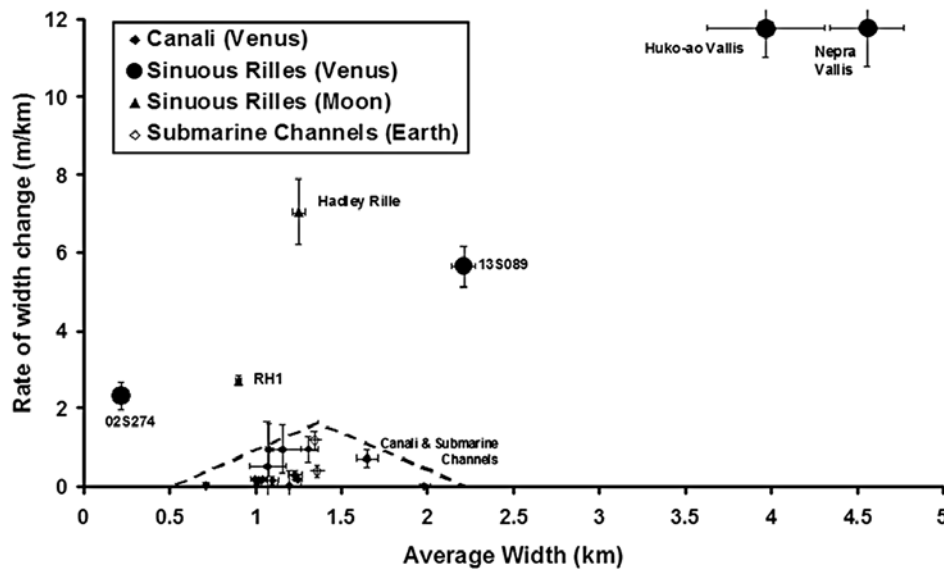


Figure 2. Rate of width change as a function of average width for Venusian canali [from Bray *et al.*, 2007] and for the most distal 450 km of the Amazon [Pirmez and Imran, 2003] and Zaire [Babonneau *et al.*, 2002] submarine channels on Earth. For comparison, Hadley Rille and RH1 [Greeley and Spudis, 1978] for the Moon, together with four rilles from Venus, are also plotted. Error bars show 1SE uncertainties.

2.2. Channel Width

[9] A defining characteristic of canali-type channels is the remarkably consistent widths along their lengths [e.g., Baker *et al.*, 1997]. The Venusian canali used in this study (data from Bray *et al.* [2007]) have average widths and rates of change in width shown in Figure 2. Figure 2 also shows statistics for the Amazon and Zaire submarine channels (data from Pirmez and Imran [2003] and Babonneau *et al.* [2002], respectively) and for several sinuous rilles on Venus and the Moon (including “RH1” taken from Greeley and Spudis [1978]). Note that the typical widths, and the typical rate of change in width, have similar values for all the canali studied and that these are very similar to the values for submarine channels. Sinuous rilles, on the other hand, have a wider range of widths than canali and these typically change with distance at a rate which is an order of magnitude faster than canali.

[10] However, it should be noted that only the most distal 450 km of the Amazon and Zaire channel data have been used in Figure 2. The proximal parts of submarine channels on Earth do not have constant widths (Figure 3a). Instead, they show an initially rapid decrease in width, followed by a long, constant-width zone in the more gently sloping distal regions. In the Amazon channel case the width is almost perfectly constant between 400 km and 650 km but then shows a gentle increase. The Zaire channel width profile is very similar to the Amazon channel with a sharp fall in width out to 400 km and then a near-constant width thereafter [Babonneau *et al.*, 2002].

[11] Canali may well have a similar pattern of varying width when their complete profiles are visible. Figure 4 shows a channel located at 66°S, 16°E that was identified by Komatsu *et al.* [1993] as being of compound-type. We propose that this is actually a near-pristine example of a canal and that it exhibits more complex features than usual

simply because the entire channel is preserved. It shows a possible source region to the west, a terminal fan to the east and a continuous channel connecting them. The source and terminal fan will be discussed in more detail later. Here we concentrate on the channel width that has been digitized using both the left-look and right-look images (Figure 3b). Interestingly, there is a systematic tendency for the width to appear larger in the left-look image compared to the right-look (probably the result of foreshortening). Nevertheless, the trends are identical in both images. The initial 60 km shows a rapid fall in channel width at a rate of 12.3 ± 0.6 (2σ) m km^{-1} . The remainder of the channel narrows an order of magnitude more slowly with a rate of 0.8 ± 0.4 m km^{-1} which is similar to the rates shown for canali in Figure 2. The implication is that canali have constant width only in their central zones, that is, where they cross the plains and before they reach their terminal fans. However, in the vast majority of canali-type channels this is precisely the region that is preserved, thus giving rise to the near-constant width of observed canali segments.

[12] For comparison, it is worth looking at width profiles for sinuous rilles. Figure 5 shows a number of rilles located near 13°S, 89°E, and Figure 3c shows the corresponding width profile along the longest of these. The overall trend is one of approximately linear decrease in width with distance (at a rate of 6 ± 1 m km^{-1}) although there are deviations from this such as the distinct increase in width during the first 100 km. We have looked at a number of similar profiles for other rilles on Venus and the Moon, all of which show the same pattern of minor deviations from an essentially linear decrease in width with distance.

2.3. Channel Topographic Profiles

[13] Figure 6 shows the along-channel altitude variations for the Amazon channel, the canali shown in Figure 4, and

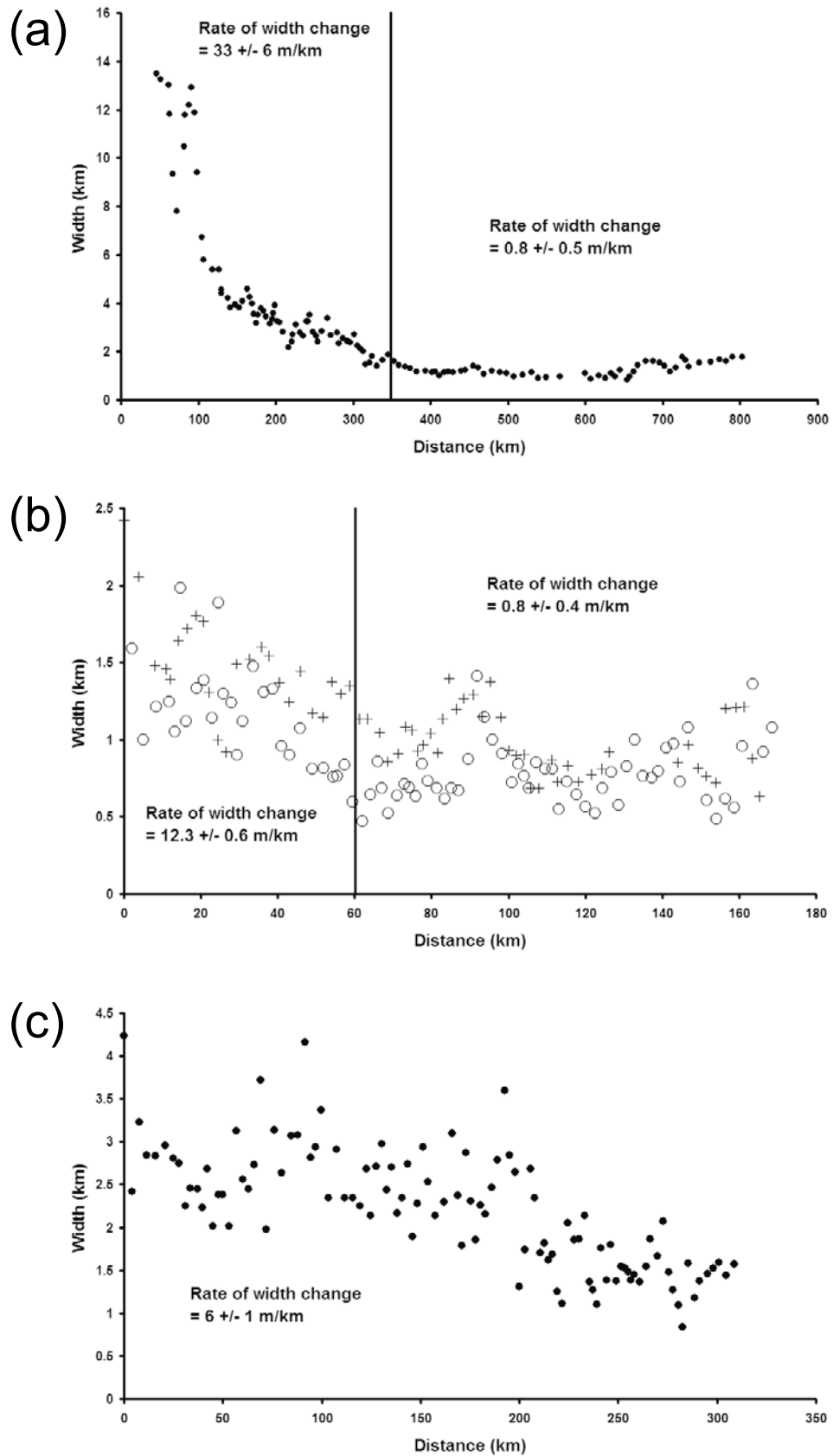


Figure 3

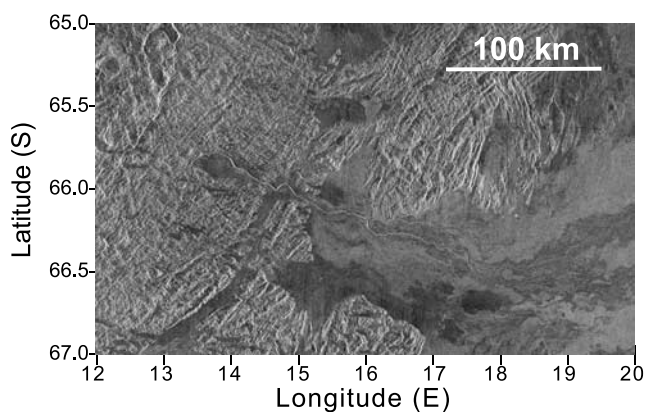


Figure 4. Possible, near-pristine and complete, canali-type channel located at 66°S, 16°E on Venus. Eastern end shows a clear terminal fan, and western end lies within a highland region. Hence flow is interpreted as being from west to east. Western end is a possible canali “source” area. Magellan right-look radar image is courtesy of NASA Planetary Data System Imaging Node, U.S. Geological Survey, Flagstaff, Arizona.

the sinuous rille shown in Figure 5. The Amazon channel and the Venusian canali-type channel show a similar pattern of decreasing slope with distance except where the terminal fan is reached on the canali (from 140 km). The Zaire channel also shows a uniformly decreasing slope with distance [Babonneau *et al.*, 2002]. The sinuous rille however shows a rather different profile with an almost constant slope along most of its length. Other rilles we have looked at show a wide variety of profiles as a consequence of postformation tectonics and are therefore of limited use for drawing firm conclusions.

2.4. Meander Geometry

[14] The relationships between meander wavelength and the radius of curvature of canali-type and other solar system channels are discussed by Baker *et al.* [1992], Komatsu and Baker [1994], Jones and Pickering [2003], and Bray *et al.* [2007]. When graphically comparing these dimensions, trend lines of volcanic channels tend to be steeper than those cut by aqueous fluids [e.g., Baker *et al.*, 1992; Bray *et al.*, 2007]. The relationship between meander wavelength and radius of channel curvature is complex as the flow properties can be affected by surface slope, local gravity, discharge rate and flow duration, among other factors. However, Baker *et al.* [1992] found a strong dependence of lava channel morphology upon fluid viscosity; this simplified relationship has subsequently been used to infer that the canali-carving fluid was of water-like viscosity [Kargel *et al.*, 1994]. Measurements from Bray *et al.* [2007] show the wavelength versus radius of curvature trend of canali to have a gradient of 0.28 ± 0.02 . These values are far shallower than the trend lines for Venusian channels of confirmed volcanic origin (gradient of $0.74 \pm$

0.11 [Bray *et al.*, 2007]). Bray *et al.* [2007] report trends similar to those of the volcanic channels for sinuous rilles from Venus (0.70 ± 0.25) and the Moon (0.72 ± 0.04). On the other hand, solar system channels showing similar meander geometry trends to canali include Martian outflow channels (0.36 [Kereszturi, 2003]), terrestrial rivers (0.2 [Leopold and Wolman, 1960; Williams, 1986]), and submarine channels (0.44 [Clark and Pickering, 1996]).

2.5. Levées

[15] Box A in Figure 1 highlights a region of a canali-type channel where it is characterized by weak radar backscattering from its centre and strong backscattering from its margins. These margins are interpreted to represent relatively rough levée deposits resulting from channel overflow followed by bank-top deposition [Bussey *et al.*, 1995]. Similar processes occur in submarine channels and can be seen in sonar images of the seafloor. Figure 7 shows a SeaMARC side-scan sonar image of the Mississippi fan which lies 3000 m below the surface of the Gulf of Mexico (see Twichell *et al.* [1992] for details of the imaging). The Mississippi fan data is characterized by weak (acoustic) backscattering from the channel and strong backscattering from a narrow zone on the channel margins. Thus the Venusian and Mississippi examples show similar levée characteristics, although it should be noted that open-lava channels (but not lava tubes) also create levées [Bussey *et al.*, 1995].

2.6. Terminal Fans

[16] Figure 8 shows a comparison between the terminal fan of the Mississippi channel (redrawn from Twichell *et al.* [1992]) and the terminal fan of the canali-type channel shown in box B of Figure 1. The key feature to note here is that both fans are constructed from interfingering, occasionally anastomosing, channels which are individually flanked by radar/acoustically rough deposits. The frequency of branching and the angles between the branches are also similar in both fans. Neither fan shows sheet-flow deposits, that is, deposits not directly associated with a feeder channel. Similar fans are characteristic of other submarine channels on Earth and of several canali-type channels on Venus (e.g., see Figure 4). Similar-scale fan-like features are associated with the terminus of lava distribution systems on Earth (e.g., Hawaii and Etna) but produce topographic slopes which are 2 orders of magnitude steeper than those seen on Venus. Hence these terminal fans are inconsistent with basaltic lavas transported through lava tubes.

3. Are Particulate Gravity Currents Plausible on Venus?

[17] This section considers whether it is possible for particulate gravity currents to exist in the physical and geological conditions of Venus, which are very different to those in which terrestrial submarine channels form. First we look at the physics of such flows and show that a channelized gravity current formed by sand-sized particles

Figure 3. Plots of channel width versus along-channel distance for (a) the Amazon Channel on Earth (data from Pirmez and Imran [2003]); (b) possible, near-pristine, canali-type channel at 66°S, 16°E on Venus (see Figure 4); and (c) sinuous rille at 13°S, 89°E on Venus (see Figure 5). Crosses in Figure 3b are left-look data, and circles are right-look data.

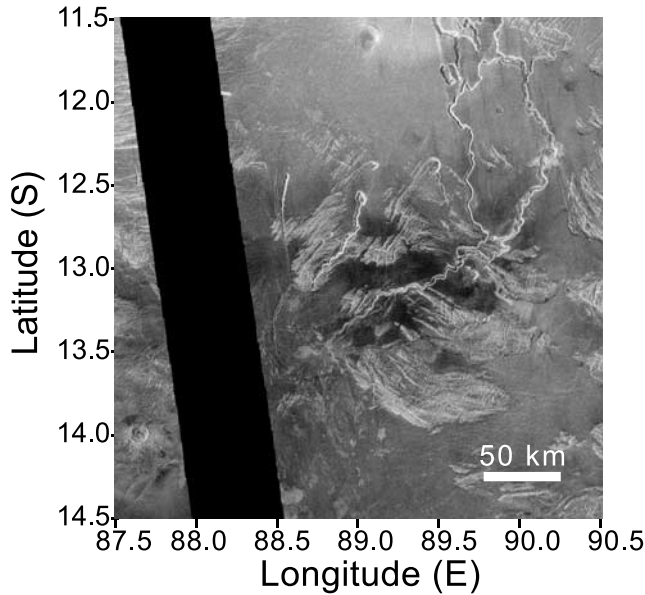


Figure 5. Sinuous rilles located at 13°S, 89°E on Venus. The longest example shown here was used to produce Figures 3c and 6c. Magellan radar image is courtesy of NASA Planetary Data System Imaging Node, U.S. Geological Survey, Flagstaff, Arizona.

suspended in the dense atmosphere of Venus can flow distances of thousands of kilometers. We then look at the geological conditions necessary to initiate such flows and show that suitable conditions exist on Venus.

3.1. Physical Plausibility

[18] We assume that the flow can be approximated by a steady current and that particle suspension results from turbulence in the flow. We also assume that, for a flow to be sustained, the basal shear stress of the flow must be sufficient to reentrain any particles that drop out of the flow so that flow density is maintained by dynamic equilibrium between particle deposition and particle reentrainment. Hence our criterion for flow plausibility is that turbulence, together with basal shear stress, is sufficient to maintain appropriate sized particles in the flow. We show below that this criterion works for two very different types of particulate current on Earth and that the predicted maximum grain diameters agree reasonably with observations. The simplicity of our model, and hence its small number of parameters, allows estimates to be made of appropriate parameters in the very different conditions on Venus.

[19] The assumption of a steady flow is reasonable given the uniform geometry of canals along their great lengths and it is consistent with the assumption that canal flows have similar durations to terrestrial turbidity currents. It should be noted that a steady-flow model also assumes that momentum is insufficient to carry such flows over very long distances and that these flows are driven by pressure gradients. These pressure gradients are produced by a sloping flow top which, for the special case of a steady uniform flow, will have the same gradient as the channel floor.

[20] Given a steady state, a force balance between gravity and friction gives

$$\tau = c\Delta\rho ghH', \quad (1)$$

where τ is the basal shear stress, c is volumetric concentration of particles, $\Delta\rho$ is the density excess of the particles compared to the ambient fluid, g is the acceleration due to gravity, h is the flow thickness, and H' is the flow-top gradient. Equation (1) is similar to standard expressions for flow in open channels [e.g., see *Duncan et al.*, 1960] except that the density excess of the flow has been expressed in terms of the concentration and density of the grains making up the particulate flow. The shear stress in equation (1) may be compared to Shields' criterion that reentrainment of loose grains will occur provided [*Raudkivi*, 1998]

$$\tau > \theta\Delta\rho gD, \quad (2)$$

where θ is Shields' parameter (~ 0.05 across a wide range of grain diameters) and D is the grain diameter.

[21] To calculate the maximum suspended grain diameter we note that for a turbulent flow the shear stress can be represented by an equivalent shearing velocity, u_* , defined by [*Raudkivi*, 1998]

$$\tau = \rho u_*^2, \quad (3)$$

where ρ is the bulk density of the flow. Combining equations (1) and (3) then yields [cf. *Kneller*, 2003]

$$u_* = \sqrt{g'hH'}, \quad (4)$$

where g' is the reduced gravity (defined by $g' = gc\Delta\rho/\rho$). For suspension, the turbulence-generated root-mean-square fluctuations in vertical velocity should exceed the fall velocity (from *Raudkivi* [1998] but see *Leeder et al.* [2005] for a critique) and laboratory studies [e.g., *Bagnold*, 1966; *Kneller et al.*, 1999] show that the RMS fluctuations are of similar magnitude to the shearing velocity. An entirely equivalent suspension criterion is that the Rouse number should be less than 2.5 [*Rouse*, 1937; *Allen*, 1997] since this also leads to the expectation of a suspension threshold when fall velocity approximately equals the shear velocity. Thus, using Stokes' Law to estimate the fall velocity, equation (4) leads to a suspension criterion that

$$D^4 \leq \frac{18^2 c H' \mu^2 h}{\rho \Delta \rho g}, \quad (5)$$

where μ is the dynamic viscosity of the ambient fluid. Note that expression (5) is based on two experimentally confirmed fluid-dynamics approximations; one that relates shear stress to turbulence and another that relates fall velocity to particle size. The only additional assumption is that we have a uniform, steady current. The robustness of the resulting expression can be emphasized by testing it against Earth-bound particulate currents.

[22] Using parameters appropriate for site ODP 934 in the Amazon Channel (see Table 1; values taken from *Pirmez and Imran* [2003]), expression (5) predicts a maximum

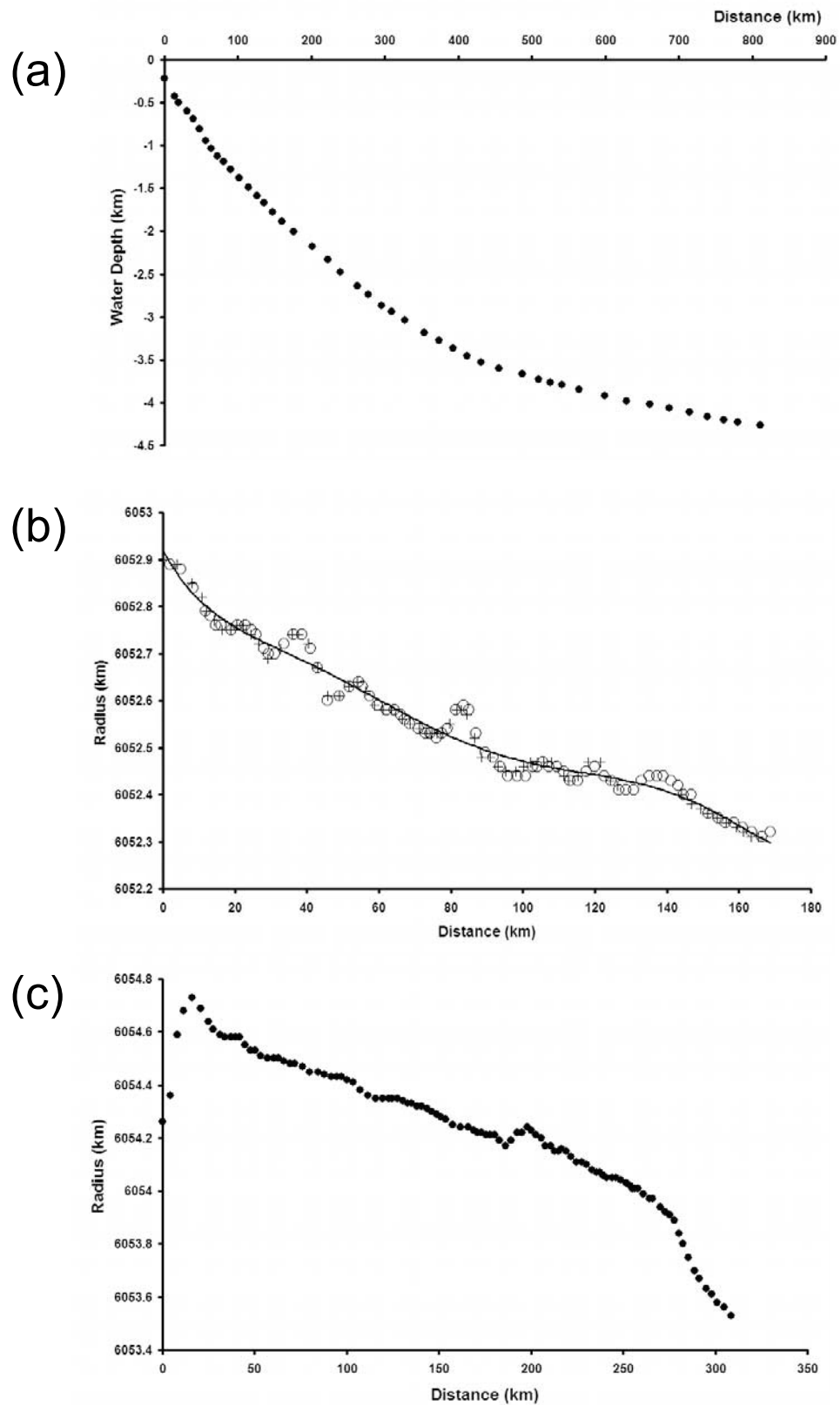


Figure 6. Plots of channel height versus along-channel distance for (a) the Amazon Channel on Earth (data from *Pirmez and Imran* [2003]); (b) canali-type channel at 16°S , 16°E on Venus (see Figure 4); and (c) sinuous rille at 13°S , 89°E on Venus (see Figure 5). Venusian profiles are expressed in terms of radius from center of planet. Crosses in Figure 6b are left-look data, and circles are right-look data. Line in Figure 6b shows best fit sixth-order polynomial.

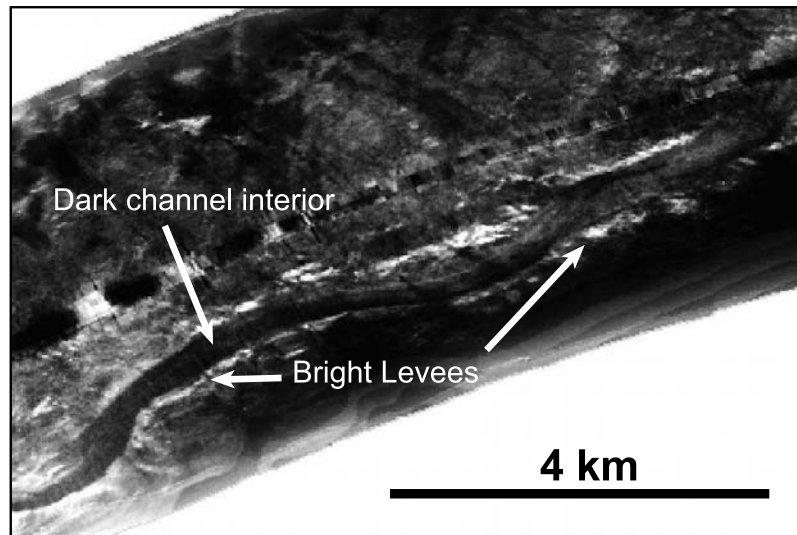


Figure 7. SeaMARC side-scan sonar image of part of the Mississippi fan below the Gulf of Mexico (water depth of 3000 m). Highly reflective, levée deposits flank the relatively unreflective channel interior (compare with box A in Figure 1). Data are from *Twitchell et al.* [1992].

suspended grain size of 560 microns. *Pirmez and Imran* [2003, Figure 10] show channel fill deposits at site ODP 934 with a maximum grain size of $\phi \sim 0.8$ (i.e., 570 microns). Thus expression (5) accurately predicts the observed maximum grain diameter for the Amazon channel case. Furthermore, equation (2) predicts that the basal shear stress will exceed the threshold for reentrainment by a factor of sixty, so

there is no problem with reentraining deposited grains back into the flow.

[23] Pyroclastic surges from Earth volcanoes are particulate gravity flows with very different parameters than those of a turbidity current. Generally, pyroclastic deposits result from a complex interaction of a dense granular flow overlain by a less dense turbulent surge [*Sheridan*, 1979; *Hopfinger*, 1983; *Takahashi and Tsujimoto*, 2000].

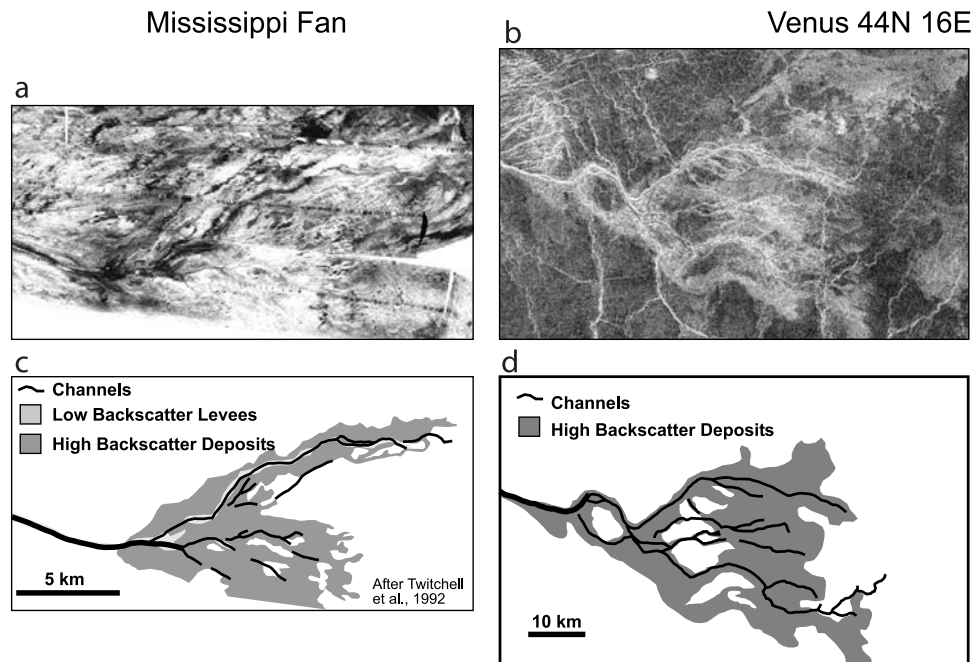


Figure 8. (a–d) Terminal fans for the Mississippi fan and for the canali-type channel shown in box B of Figure 1. Figures 8a and 8b are side-scan sonar and Magellan radar images, respectively. Geological interpretations in Figures 8c and 8d indicate similar morphologies with branching, interfingering, and anastomosing channels flanked by bright deposits. Mississippi fan data and interpretation are after *Twitchell et al.* [1992].

Table 1. Parameters and Results for Modeling of Particulate Gravity Currents on Earth and on Venus

| | Merapi Pyroclastic Surge | Amazon Channel | Venus |
|------------------------------------|--------------------------|-----------------------|-----------------------|
| <i>Model Parameters</i> | | | |
| μ Pa s | 1.90×10^{-5} | 1.52×10^{-3} | 2.50×10^{-5} |
| $\Delta\rho$, kg/m ³ | 2600 | 1500 | 2700 |
| h , m | 50 | 50 | 30 |
| c | 0.00046 | 0.01 | |
| ρ_{fluid} , kg/m ³ | 0.74 | 1030 | 65 |
| H' | 0.17 | 0.004 | 0.004 |
| g , m/s ² | 9.81 | 9.81 | 8.87 |
| <i>Model Predictions</i> | | | |
| ρ_{flows} , kg/m ³ | 1.94 | 1035 | |
| D , μm | 310 | 560 | |
| $\tau/\tau_{shields}$ | 252 | 71 | |
| <i>Observations</i> | | | |
| D , μm | 380 | 570 | |

However, these two components can become spatially or temporally separated allowing pristine surge deposits to be identified. The Merapi volcano nuée ardente of 22 November 1994 produced such deposits and these have been studied by *Abdurachman et al.* [2000], *Kelfoun et al.* [2000], and *Clarke and Voight* [2000]. Using the parameters reported in these studies (see Table 1), equations (1), (2), and (5) predict a maximum grain size of 310 microns and that the basal shear stress exceeds the threshold for reentrainment by a factor of 250. The observed maximum grain size was 380 microns which is in excellent agreement with the prediction given that it is based on a very simplified, order-of-magnitude, model.

[24] The success of our model with two very different Earth-bound examples gives confidence that it should also work for particulate currents on Venus. The parameters used for the proposed Venusian currents are given in Table 1. Flow thickness was estimated from the depth of the channels [*Komatsu et al.*, 1992; *Baker et al.*, 1997] and grain density assumed a basaltic composition [*Surkov et al.*, 1986], while the density and viscosity of the atmosphere were assumed to be those of carbon dioxide at Venusian surface temperatures and pressures [*Reid et al.*, 1987]. Flow

concentration is not known and so we assumed a range from 0.1 to 0.0001 which covers a range much wider than is typical for turbidity currents or pyroclastic flows. Note, however, that the water-like viscosity inferred from the meander geometry implies that the effective viscosity of the flow is much higher than that of CO₂ which, in turn, suggests that the higher particulate concentrations in this range are more likely. Also note that the viscosity used in expression (5) is that of the ambient fluid and so our results are not invalidated by this conclusion. A slope of 0.004 was estimated from the profile shown in Figure 6b. Figure 9 was produced using these parameters together with equations (1), (2), and (5). Note that basal shear stress comfortably exceeds the Shields' threshold for all concentrations. However, even for the most optimistic estimate of flow concentration, the maximum suspended grain diameter is significantly finer than for flows within submarine channels on Earth. Nevertheless, it is clear that fine-grained particulate gravity flows are physically possible under Venusian conditions.

[25] A further constraint on flow concentration (and hence suspended grain size) can be obtained by comparing the size of the turbulent velocity fluctuations approximated by equation (4) to ambient wind fluctuations of $\sim 0.2 \text{ ms}^{-1}$ reported by *Kerzhanovich and Marov* [1983]. For the proposed Venusian particulate gravity currents, predicted turbulent fluctuations range from 0.057 ms^{-1} for $c = 10^{-4}$ to 1.8 ms^{-1} for $c = 0.1$ and only exceed the ambient fluctuations for concentrations above 0.001. Thus the very low concentration (i.e., $c < 0.001$) flows seem to be ruled out by the fact that any particulate-current deposits would be resuspended by atmospheric turbulence thus disrupting channel formation by aggradation.

[26] The steady state model used above implies that channelized particulate gravity currents will flow indefinitely provided a sufficient slope is maintained. In this model, flows die out distally only because slopes fall off. Note that rivers on Earth flow indefinitely rather than stopping after traveling some arbitrary distance. Particulate currents only differ in that they require a grain-size-dependent minimum slope to provide sufficient turbulent energy to maintain

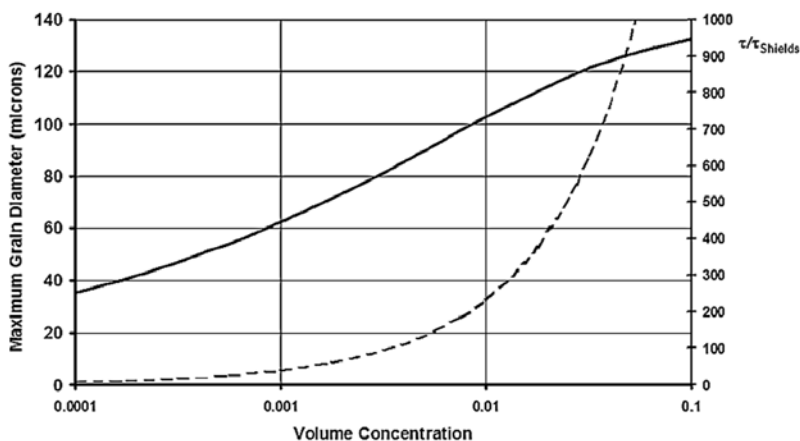


Figure 9. Predicted maximum grain diameter for particulate gravity currents in Venusian Canali (solid line). Flow concentration is unknown but unlikely to fall outside the range used here. Other model parameters are well constrained (see text for details). Graph also shows the predicted basal shear stress as a multiple of the minimum stress for particle reentrainment (dashed line).

suspension. Expression (5) predicts a fairly weak dependency of maximum grain size on slope so that, for example, a reduction in slope by a factor 4 (to 0.001) would reduce the diameter of the largest supported grains by a factor of only $4^{1/4} \sim 1.4$. Even lower slopes would be allowed if, as seems reasonable, the channel depths at the time of formation were deeper than presently preserved. Slopes of 0.001 or less imply altitude drops of kilometers over distances of thousands of kilometers. Hence, given that Venusian topography covers a range of around 4 km, particulate gravity currents can easily cover the thousands of kilometers necessary for them to be considered a candidate process for canali formation.

3.2. Geological Plausibility

[27] The presence of loose particulate matter on the Venusian surface is irrefutably demonstrated by the presence of more than 6000 aeolian features, such as dune fields, yardangs and wind streaks [Greeley *et al.*, 1997]. These features are distributed across the plains areas of Venus but show no clear relationship with canali. The existence of small amounts of fine material is also consistent with radar backscatter data, which demonstrates that Venusian plains are smooth at meter scales [Ford and Pettengill, 1992; Campbell and Campbell, 1992] possibly indicating mantling by submeter diameter particles. It is also worth noting that Venera surface panoramas show a fine-grained, porous soil filling spaces between the larger rocks [Florenskiy *et al.*, 1983] and that the cloud of dust formed at touchdown by these probes requires the presence of particles smaller than ~ 0.02 mm [Basilevsky and Head, 2003]. However, the pristine appearance of geological features at the Magellan radar resolution of ~ 100 m, argues against a deep planet-wide regolith. The overall picture that emerges is of locally significant, although globally small, quantities of sediment being present on the Venusian surface.

[28] On Earth the particulate material, which goes on to produce turbidity currents, first accumulates near continental margins as a result of river transport from continent interiors. Continuing accumulation eventually leads to oversteepening followed by catastrophic collapse and this process generates a succession of turbidity currents. A similar mechanism is not possible on Venus because there is no known equivalent to river transport within the highland areas. Instead, we propose here that canali source regions are associated with localized areas of tectonic deformation which episodically generate clouds of suspended particulate material as a consequence of fault-scarp collapse.

[29] Large dry-rockslide avalanches on Earth [Mudge, 1965; Hsü, 1975; Voight *et al.*, 1983; Ui, 1983; Siebert, 1984; Schneider and Fisher, 1998] can produce 10^3 s of km^3 of material containing decimetric to micrometric sized particles transported 10^3 s of kilometers from their sources. In the case of the Miocene collapse of Cantal Volcano (France) the resulting deposits were matrix supported [Schneider and Fisher, 1998] indicating that a substantial fraction of this debris consists of fine-grained material. Photomicrographs showed that the matrix grains had typical diameters in the 10–100 μm range. Similarly, Hsü [1975, p. 135] describes rockfall deposits in the Alps where the deposits consist of “large angular blocks embedded in a

matrix of fine rock flour” again implying that gravitational collapse of steep slopes on Earth produces substantial volumes of fine particles.

[30] Venus has many tectonic features which could act as such source areas because the plains are surrounded by extensive high-relief regions that are up to ~ 4 km higher than the plains. For these to act as sources it is necessary for them to be tectonically active during plain formation as suggested by Hansen *et al.* [1997]. Given this model, canali should show a pattern of drainage away from highland regions and toward plain interiors.

[31] As discussed earlier in section 2, Figure 4 shows the only example known to the authors of a canali-type channel, which seems to have been completely preserved so that it shows both its source and its termination. The terminal fan forming the eastern end of the channel is comparable in morphology to those shown in Figure 8. Thus this canal appears to have flowed from west to east. It would also seem sensible that, whatever the true nature of canali currents, they flowed from high areas toward lower ones and the western end of this canali-type channel lies within a highland region (see profile in Figure 6b). Hence we are confident that this particular canali-type channel flowed from west to east and that its western end represents the source region of the channel.

[32] Figure 10 shows a close-up of the proposed source area along with a 3-D shaded relief view showing the relationship of this source to the surrounding topography. It is immediately apparent that the source is a relatively flat-lying minibasin forming a reentrant with hills to the north, west and south and an exit to the east. We therefore propose that particulate gravity currents were generated by repeated, catastrophic fault-scarp failures in the surrounding hills which “drained” into the minibasin and then flowed out through the eastern exit. Note that this reentrant geometry provides a natural mechanism for focusing the sediment supply onto a single channel.

[33] The larger clasts in the resulting landslides would have traveled a similar distance to large rockfall avalanches on Earth (tens of kilometers) and so would have remained within the minibasin and partially infilled it. However, a proportion of the finer particles would have formed particulate clouds above the landslides (similar to pyroclastic surges riding on underlying pyroclastic flows) which could travel independently after the landslide motion had stopped. Hence this reentrant formed a consistent source location for multiple fine-particulate flows along the associated channel.

[34] Note that the surface area covered by the proposed source region (i.e., the entire upslope zone surrounding the minibasin) is only a little smaller than the plains area likely to have been affected by deposition from the channel. Thus an average of a few hundred meters of denudation in the source region is all that is necessary to generate a hundred meter thick deposit on the plains. Note also that this implies channel formation, on the plains, by an aggradational rather than erosional mechanism.

4. Discussion

[35] We have considered six morphological properties of canali, submarine channels and sinuous rilles. Of these, four (length, width/width change, sinuosity, and slope profile)

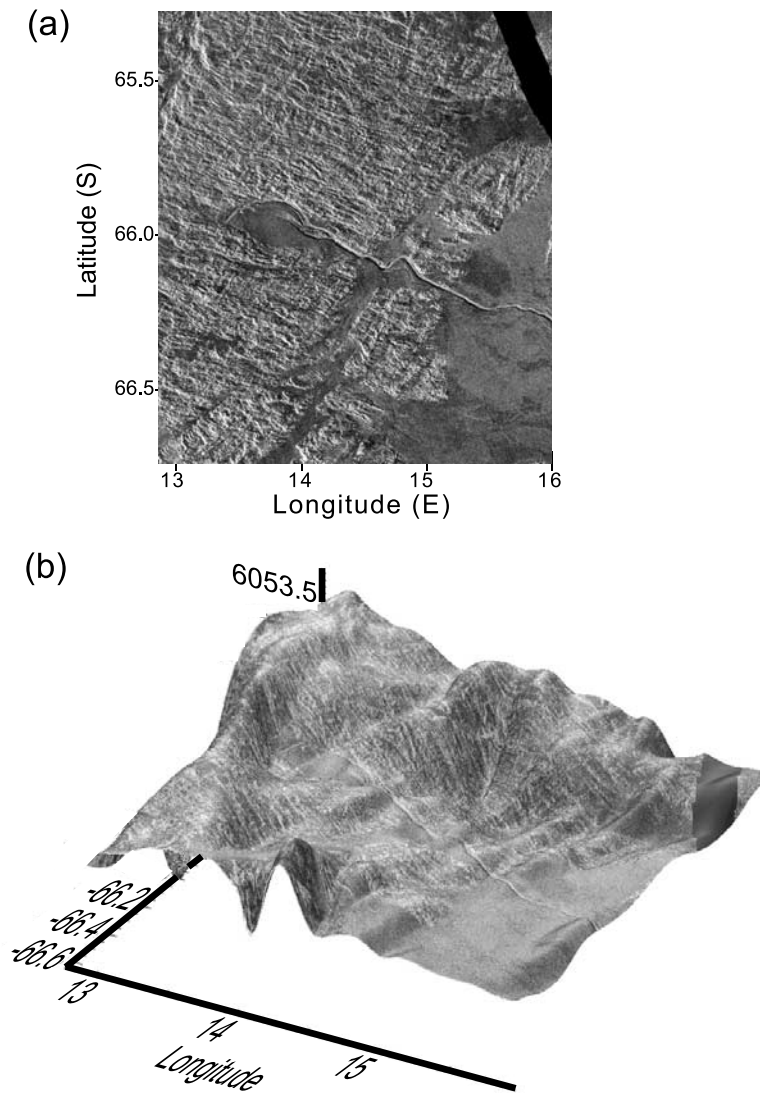


Figure 10. (a) Close-up of the canali-type channel source region from western end of Figure 4. (b) Image from Figure 10a superimposed on shaded-relief Magellan topography. Magellan radar image is courtesy of NASA Planetary Data System Imaging Node, U.S. Geological Survey, Flagstaff, Arizona.

show great similarities between canali and submarine channels while two (the existence of levées and terminal fans) show similarities between all three channel types. However, the existence of shallow-gradient terminal fans and the existence of levées, together with the absence of clear tube-collapse features on canali, argues against a lava-tube hypothesis. In addition, the absence of a mechanism for generating large quantities of exotic, low-viscosity, lava is a serious problem for most explanations involving open-channel lava flows. Unless these problems can be resolved, current lava based models cannot provide an adequate mechanism for canali origin. As such, we consider particulate gravity currents a well-supported alternative explanation for canali formation. This paper has demonstrated that particulate gravity currents are physically sustainable within the present Venusian atmosphere and that a plausible

geological mechanism exists for creating source regions for these flows.

[36] An interesting point that follows from our particulate gravity current proposal is the question of why there are no canali in the process of formation today. However, new canali only need form every few million years to account for the observed numbers of canali given the crater-count-derived average age of the Venusian plains. Submarine channels on Earth form over periods of tens to hundreds of thousands of years and, if canali have similar lifetimes, then it is unlikely that we would see active canali formation at any particular moment in time. However, we would expect to see canali in a range of different states of preservation, exactly as seen in practice, although the preponderance of poorly preserved canali segments probably supports the widely held view that Venus is, tectonically, fairly quiescent at the present day so that most

canali are relatively old. It should also be noted that most landslides would occur in settings that do not have the fortunate “focusing” geometry of the reentrant topography discussed earlier. Hence landslides will not usually be able to generate repetitive particulate flows concentrated into a small area and canali formation will be a relatively unusual result of landslide processes.

[37] A further prediction of our proposal is that canali sources should lie within highland areas rather than arising within the plains themselves. This is a difficult prediction to verify because of the incomplete preservation of most canali but it is certainly true that three out of the four regions of high canali concentration identified by Komatsu *et al.* [1993] are adjacent to highland areas rather than lying in more “distal” locations.

[38] The main conclusions from this paper are that particulate gravity flows are possible on the Venusian surface and may explain the origin of canali. We should make it clear that, at present, these are no more than tentative hypotheses. As the origin of these enigmatic channels remains in doubt, we put forward the particulate gravity current proposal in the hope that others will find it a useful stimulus for further work or for suggesting other alternatives. Further progress on this is hampered by the limited resolution of the current data. In particular, higher-resolution imaging of the area shown in Figure 10 would allow our suggestion that it is a canali source to be more rigorously tested and it would allow our characterization of the area as dominated by fault-scarp collapse to be confirmed or refuted. In any event, we look forward to seeing alternate interpretations of this “source.” The lack of widely acknowledged canali-source features is a major handicap to all models of canali formation since many of the current candidate explanations for these channels (e.g., exotic lavas or water) seem to require unusual source conditions.

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