COMPOSITIONAL CONSTRAINTS ON OUTFLOW CHANNEL-FORMING LAVAS ON VENUS;
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Introduction. Magellan images of Venus reveal a variety of large "outflow channels" exhibiting very fluvial-like morphologies, including meanders, cutoff meander loops, anastomosing, braiding, delta-like distributaries, and streamlined erosional remnants and depositional channel bars [1]. Many of these channels originate at fractures in volcanic terrains and terminate in lava "deltas". Given present surface conditions on Venus we do not seriously consider a fluvial origin, and instead seek a suitable volcanic explanation. Volcanic channels exist on Earth and Moon, and some exhibit meanders and other fluvial-like features, but none of the terrestrial or lunar volcanic channels exhibits the full degree and range of morphologic characteristics shown by the more complex venusian channels. Large terrestrial river channels such as the Yangtze and Mississippi are much better morphologic analogs.

Rheologic contraints on composition. Channelforms and bedforms on Venus, like their terrestrial fluvial and volcanic counterparts, must be the products of erosion and deposition by turbulent flows, the character of which depends substantially on the fluid's viscosity. Low viscosity directly promotes turbulence and high lava eruption rates, hence, deeper, faster, and more erosive flows. Deposition of suspended crystals is also encouraged by low fluid viscosities, as is hydrodynamic shaping of channel deposits. We postulate that Venus' fluvial-like outflow channels were formed by flows which behaved dynamically more like stream flows on Earth than basalt flows, thus indicating a rather "watery" rheology. Few volcanic liquids have viscosities substantially lower than terrestrial basalt, so we have an opportunity to constrain the possible compositions of venusian channel-forming lavas. Volcanic channels on Earth, Moon, and Venus appear to form a morphologic continuum ranging from short, linear collapsed lava tubes common in basaltic terrains on Earth, through sinuous and occasionally anastomosing volcanic rilles on the Moon, to complex braided and fully fluvial-appearing channels most characteristic of Venus. Figures 1 and 2 illustrate the viscosities of candidate lavas (appropriate for the liquidi of anhydrous lavas, and an absence of crystals, except for the viscosity of sulfur, which applies to Venus surface temperature; constructed from many sources including references 2, 3, and 4; contact first author for more references and details). Figure 2 reflects the well known fact that the viscosities of silicates are closely correlated with composition, represented here by $(MgO + FeO)/SiO_2$ (in weight percent).

Fluid density, ρ, and surface gravity, g, have effects on flow turbulence opposite to viscosity, and can be included in a "mobility index" (MI), defined as: $MI = \log_{10}(\rho g/\mu)$. MI derives from solutions to basic fluid dynamics problems such as that giving the flow velocity in a channel or on an inclined plane. Other factors, such as flow depth and the size of sediment grains, are also dynamically important, but are not intrinsic properties of the fluid or planet, and are not considered. MI is plotted in Figure 3 for several lavas against $\log_{10}(g)$. While the choice of plotting parameters ensures a linear relationship for each liquid, Figure 3 allows easy planetological comparisons of MI. The viscosities are appropriate for pure liquids (crystal-free) at their melting points, except for sulfur, the viscosity of which corresponds to the venusian surface temperature. Figure 3 shows that basalts on Earth have MI $\sim$ 0.7 - 1.7, and Fe-Ti basalt on the moon has MI $\sim$1.8. We suggest that venusian channels were carved by fluids more fluid than lunar basalt on the Moon, *i.e.*, with MI > 2.5. From Figure 3 we find that Fe-Ti "lunar" basalt (on Venus), komatiite, and sulfur would be rheologically acceptable. Carbonatite probably also would have MI > 2.5. Silicic lavas, tholeiitic and alkali basalt, and picrite all seem too "stiff". The Venus surface compositional analysis by the VEGA-2 lander has $(MgO + FeO)/SiO_2 = 0.42$ [5], and would not allow sufficient fluidity to form outflow channels. Thus, if the channel-forming fluids were silicate, they were probably high-temperature ultramafic lavas with $(MgO + FeO)/SiO_2 > 0.6$ (by mass), consistent with terrestrial komatiite or lunar Fe-Ti basalt. Alternatively, the lavas may have had nonsilicate compositions such as sulfur or carbonatite.

Discussion. The immense scale of the largest outflow channels and associated lava deltas implies huge discharged volumes, favoring a magma source in the mantle rather than the crust. An ultramafic silicate lava would imply high degrees of partial melting at high temperatures, and could involve large volumes of the mantle. On the other hand, carbonatite or sulfur would imply low degrees of partial melting at low temperatures, probably with a crustal magma source. Thus, it is probably easier to explain the large volumes of lava if it is mantle-derived komatiite. While nowhere erupted on Earth today, komatiite was one of the most abundant lava types during the Archaean when heat flow was much greater than today. We note that the low viscosity of komatiite can be manifested in turbulent-thermal incision of channels into subjacent rock and sedimentary-like accumulations of crystals on komatiite channel floors [6], constituting "fluvial-like" phenomena not usually described from basaltic flows.

Sulfur is a very rare lava on Earth. The plausibility of high volume sulfur eruptions on Venus rests on a much higher abundance of sulfur in Venus' mantle and crust than in Earth's, probably occurring as sulfides such as pyrrhotite ($Fe_{1-x}S$) and sulfates such as anhydrite ($CaSO_4$) [7]. Interestingly, the Vega-2 lander found nearly 2% S in Aphrodite Terra [5]. A S-rich crust would require retention of a larger fraction of S in the mantle during core formation than was the case for Earth. A S-poor core could explain the absence of a strong magnetic dipole on Venus. Sulfur on Venus would resemble water (on Earth) more than basalt in terms of its fluid dynamical behavior and volatility. Sulfur flows, containing a few percent FeS, would pond in depressions and remain liquid until it evaporated over a period of months; the last dregs of liquid would become strongly enriched in FeS and other less volatile minor components, and at some point would begin crystallizing iron sulfide, which, over geological time, would oxidize to a magnetite-rich deposit. Atmospheric sulfur would react with crustal silicates, forming Ca- and Mg-sulfates at low elevations and sulfides at high elevations, possibly explaining the radar-bright region of Maxwell Montes.

Carbonatite is one of the rarer magma types on Earth, although locally is abundant. Carbonatite is generally mantle-derived, usually is associated with alkaline silicate volcanism, and is known from certain terrestrial shield areas, oceanic hotspots, and parts of the East African Rift. A variety of qualitative geological and experimental evidence suggests very low viscosities for carbonatite, although actual measurements are lacking. Dry Ca-Mg carbonates melt near 1400 K, and alkali carbonatite melts near 940 K. Such low melting points allow the generation of carbonatite magma with little or no melting of silicates and argue strongly that the mantles of Earth and Venus should be severely depleted in CO_2. Relatively small quantities of carbonate liquid could be derived from the venusian mantle or crust, but quantities large enough to form outflow channels seem more doubtful.

Conclusions. Venusian outflow channels, resembling large water-eroded channels on Earth and Mars, were apparently carved by large, sustained discharges of highly fluid lava, perhaps komatiite or sulfur, or, less likely, carbonatite.

References. 1. Gulick, V.C., et al. and Komatsu, G. et al., 1991, ABSTRACTS, this volume. 2. Bacon, R.F. and R. Fanelli, 1943, J. Am. Chem. Soc. 65, 639-648. 3. Murase, T. and A.R. McBirney, 1970, Science 167, 1491-1492. 4. Cox, K.G. et al., 1979, The Interp. of Igneous Rocks, George Allen and Unwin, Boston, 450 pp. 5. Surkov, Yu., et al., 1986, Proc. 17th Lun. Planet. Sci. Conf., J. Geophys. Res. 91, 215-218. 6. Huppert, H.E. et al., 1984, Nature 309, 19-22. 7. Lewis, J.S. and F.A. Kreimendahl, 1980, Icarus 42, 330-337.

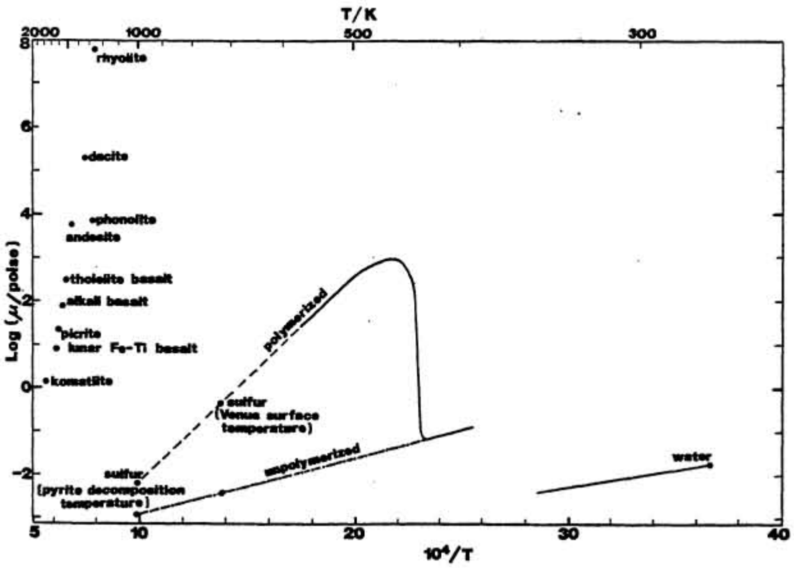

Figure 1. Viscosities of dry lavas. See text and contact first author for details.

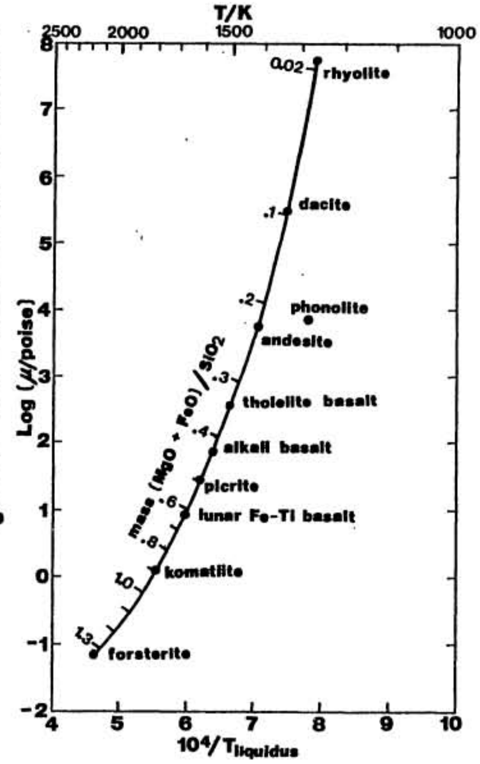

Figure 2. Viscosities of dry silicate lavas.

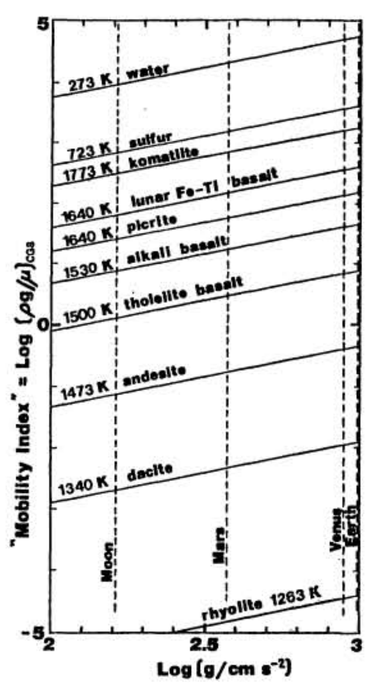

Figure 3. Relative mobility of lavas.