solar radiation, the actual solar flux required to create "moist" or "runaway" conditions would be higher than the values quoted above. (Indeed, some authors [12] have argued that cloud feedback would prevent a runaway greenhouse from ever occurring.) Early in solar system history, solar luminosity was about 25% to 30% less than today, putting the flux at Venus' orbit in the range of 1.34 S\textsubscript{0} to 1.43 S\textsubscript{0}. Thus, it is possible that Venus had liquid water on its surface for several hundred million years following its formation. Paradoxically, this might have facilitated water loss by sequestering atmospheric CO\textsubscript{2} in carbonate rocks and by providing an effective medium for surface oxidation.

Continued progress in understanding the history of water on Venus requires information on the redox state of the atmosphere and surface. The loss of an ocean of water (or some fraction thereof) should have left substantial amounts of oxygen behind to react with the crust. This oxygen would presumably be detectable if we had core samples of crustal material. Barring this, its presence or absence might be inferred from accurate measurements of lower atmospheric composition. Another spacecraft mission to Venus could help to resolve this issue and, at the same time, shed light on the question of whether clouds will tend to counteract global warming on Earth.


\[
\sigma_{c_B}(\nu) = M^{1-a} \tag{1}
\]

where \(\sigma_{c_B}(\nu)\) is the rms magnitude of a normalized spherical harmonic coefficient of degree 1. A concentrated flow, characterized by large segments moving together, has a steep slope, hence a high value of \(a\), while a distributed flow, with small segments, has a small value of \(a\). We cannot measure velocities directly on Venus. But in a planet dominated by a strong outer layer, in which the peak stresses are at a rather shallow depth, the magnitudes of gravitational potential \(V\) and poloidal velocity \(v_s\) are coupled [3]

\[
M(\delta V)/M(v_s) = 12\pi G \eta/g \tag{2}
\]

where \(\eta\) is the effective viscosity of the lithosphere, the ratio of stress to strain rate over long durations. The value inferred from the magnitudes \(M\) for Earth is \(4 \times 10^{21}\) Pa-s, probably most influenced by subduction zones. Support for this model is that the gravity and velocity spectra on Earth have the same slope \(n\) to two significant figures, 2.3 [3,4]. On Venus the spectral slope of gravity, \(n(\delta V)\), is appreciably lower over degrees that can be determined reliably—about 1.4 [4], strongly suggesting a more regional, less global, velocity field than on Earth.

A basic constraint on the velocity field that is somewhat independent of stresses, and thence rheology, is that, at the mantle depth where convection dominates—more than 150 km—there must be a correlation of vertical velocity \(v_B\) (coupled to the poloidal velocity \(v_s\) by continuity) and temperature variations \(\Delta T\) that lead to an integral accounting for most of the total heat delivery \(Q\) from greater depths

\[
Q = \int \rho c_B v_B \Delta T dS \tag{3}
\]

For a mean heat flow of 60 mW/m\(^2\) and average temperature variation \(\Delta T\) of 100\(^\circ\)C, equation (3) gives an estimate of 0.6 cm/yr for \(v_B\). In the Earth, plate tectonics lead to such concentrations of \(v_B\) and \(\Delta T\) at shallower depths that it is difficult to draw inferences from observed heat flow relevant to equation (3). However, the constraint exists, and its implication for the velocity spectrum of Venus should be explored.

The alimetry and imagery of Venus also indicate a regionality of Venus tectonics, even though magnitudes of velocities cannot be inferred because of dependence on unknown viscosity. For example, Maxwell Montes is comparable to the Andes in height and steepness (suboceanic). But the material subducted under the Andes clearly comes from the southeast Pacific Rise, over 4000 km away (despite the interruption of the Nazca Rise), while only 500 km from the Maxwell front is a scarp, and beyond that a much more mixed, apparently unrelated, variety of features. Clearly, Maxwell is more local than the Andes. A significant difference of Venus tectonics from Earth is the absence of erosion, which removes more than 1 km/100 m.y. from uplands.

Hypotheses for why Venus does not have crustal formation in a ridge system, but rather a more distributed magmatism correlated with a more regional tectonism, include (1) the lack of plate pull-apart due to inadequate subduction; (2) the lack of plate pull-apart due to drag on the lithosphere from higher viscosity: i.e., no asthenosphere; (3) the lesser concentration of flow from within the mantle, also due to higher viscosity; (4) lower temperatures, due to less initial heating and more effective retention of lithophiles in the crust; (5) higher melting temperatures, due to lack of water content, and (6) lower mobility of magma relative to matrix, due to (4) low
H₂O content, (b) low-density overburden, or (c) lesser horizontal length scale of flow.

Relevant to these hypotheses is that differentiation on Venus requires more than adiabatic upwelling and pressure-release melting. In models of this process on Earth [e.g., 5,6] the availability of mantle material to flow into the region is taken as given; the concern is about the rising of magma within a solid matrix, in particular, the mechanism(s) concentrating the melt in a narrow vertical slab. The viscosity of the melt, and hence its ability to separate, is affected by water content. Differentiation from a plume, without pull-apart, under a layer of higher strength or lower density (as is more likely on Venus), requires a surplus of heat, and thus is likely to lead to a large depth:diameter ratio [much thicker crust than consistent with estimates from crater counts]. Elasticity of the crust and no escape (from Earth).

The same considerations should apply in other environments. Theory predicts that volcanoes located at the altitude of Sophas Mons should have large magma chambers located at these altitudes. Not only do the evidence from the flow units suggest that such a zone is present, but the size of the magma chamber and the near-surface nature of the flow units indicates that the chamber is large (on the order of 100 km in diameter) and shallow.

In comparison to Sophas Mons, two other volcanoes at different latitudes were examined. Theory predicts that the volcano at the

![Fig. 1. Location of large volcanoes as a function of latitude. The dark shaded columns indicate where volcanoes would be located if they were randomly distributed on the surface as a function of the percentage of area at a given latitude. The striped columns show where the volcanoes actually occur. Note the paucity of volcanoes at higher latitudes and the concentration in the equatorial region of the planet.](image-url)