The Tectonics of Venus [and Discussion]

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The tectonics of Venus

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Solid Venus has several differences from solid Earth: a mild variation in topography, with marked departures of some kilometres confined to less than 10% of the surface; no interconnected system of ridges, such as would be associated with a spreading lithospheric boundary layer; a high correlation of gravity with topography; and a ratio of gravity to topography implying compensation depths in excess of 100 km for major features. This high admittance ratio implies a stiff upper mantle, as also indicated by the high depth–diameter ratio of craters. The details of Magellan radar imagery enable some inference of event sequences. The morphology generally indicates a more regional scale of change than on Earth.

The principal chronometer is impact crater distribution. The number of impact craters identified is 914, which is equivalent to about 500 Ma's infall of bodies big enough to penetrate the atmosphere. But the number of craters per unit area has but slightly more variations from the mean than random and only a mild negative correlation with topographic elevation. Only one-third of the craters evidence tectonic or volcanic modification. Hence the rate of resurfacing over the last few 100 Ma must be quite slight compared to Earth's.

The main debate is whether Venerean tectonic activity is in monotonic decline, or whether it is episodic on a 500 Ma time-scale. Evidencing some current tectonic and volcanic activity are a few limited regions of marked topographic and geoidal highs, exceeding 8 km and 80 m respectively, with steep slopes.

Clearly, plate tectonics does not exist on Venus. The underlying cause of this different evolution appears to be the lack of water. This dryness makes the upper mantle stiff enough to regionalize the tectonics and inhibit recycling of crust. The lack of water also prevents erosion and thus the recycling of secondary differentiates. These deficiencies in recycling imply a strong net upward differentiation of heat sources and a thick crust, now allowed by new results on dry diabase rheology.

1. Introduction

The scientific interest of Venus is that, despite similarity to Earth in primary properties, it has been found to be so different in many secondary properties. Often more is learned from a second experiment with minor changes in conditions that has markedly different results from the first, than from one that has similar results.

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Table 1. *Properties of Earth and Venus*

property	units	Earth	Venus
	Primary		
mass	10^{24} kg	5.97	4.87
mean radius	10^{3} km	6.37	6.05
reduced density*	10^{3} kg m^{3}	4.03	3.95
	Secondary		
sidereal rotation rate	rev/day	1.003	−0.0041
mean surface temperature	K	288	730
surface pressure	10^{6} Pa	0.1	9.0
atmosphere + ocean			
H_2O	$\log_{10}(\mathrm{kg/kg})^{+}$	−3.6	< -10
CO_2	$\log_{10}(\mathrm{kg/kg})^{+}$	−7.5	−4.0
N_2	$\log_{10}(\mathrm{kg/kg})^{+}$	−5.6	−5.6
$^{36+38}\mathrm{A}$	$\log_{10}(\mathrm{kg/kg})^{+}$	−10.5	−8.6
$^{40}\mathrm{A}$	$\log_{10}(\mathrm{kg/kg})^{+}$	−7.9	−8.5
K/U ratio		10^{4}	10^{4}
magnetic moment	T m^{3}	7.5×10^{15}	$< 3 \times 10^{11}$

*Mean density adjusted to a pressure of 10^{9} Pa, assuming all FeS and Fe in a central core.
$^{+}$Masses in proportion to planet mass.

2. General planetary properties

Table 1 summarizes the main physical and chemical properties relevant to the solid planet. Not shown in table 1 is sulphur dioxide, SO_2, measured mainly by EUV from Earth satellites. Peak abundances occurred in 1959 and 1978. After 1978, there was a decline by a factor of ten in the years 1978–1984, followed by a levelling-off (Esposito *et al.* 1988).

Gamma-ray spectrometry at five sites indicated abundances of radiogenic elements (K, U, Th) with averages and ranges similar to Earth's: a ratio of about ten between the most and the least radioactive sites (Surkov *et al.* 1987). X-ray fluorescent spectrometry by the Venera landers showed a Mg/Fe ratio slightly higher than Earth basalts. More remarkable are: (1) a range of K_2O abundance from 0.1% to 4.2%; and (2) volatile contents of 0.9–4.7% in SO_3 and 0.3–0.4% in Cl. These values pertain to cores about 1 cm deep, so there is a possibility of chemical weathering effects.

The major differences of Venus's solid surface from Earth's have been known since the Pioneer Venus (1979). Most striking in the topography, figure 1, are the confinement of marked departures of elevations from their mode to a few highlands covering less than 10% of the planet and the absence of an extensive connected ridge system, such as is characteristic of a spreading lithosphere, as under the Earth's oceans. Hence heat removal by lithospheric spreading on Venus must be less than 15% of Earth's (Kaula & Phillips 1981). In the comparison of

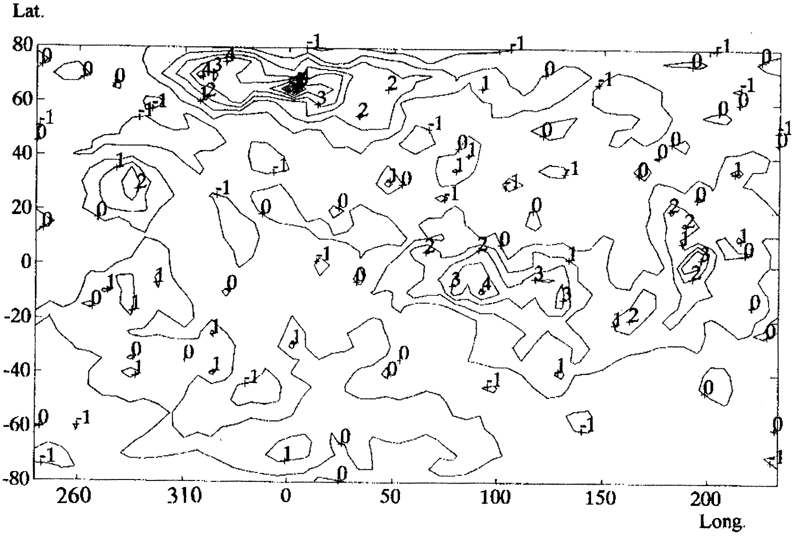

Figure 1. Topographic heights in kilometres on Venus, largely measured by Pioneer Venus altimetry (1979), but extended southward and refined in detail by Magellan altimetry (1990) (Konopliv *et al.* 1993).

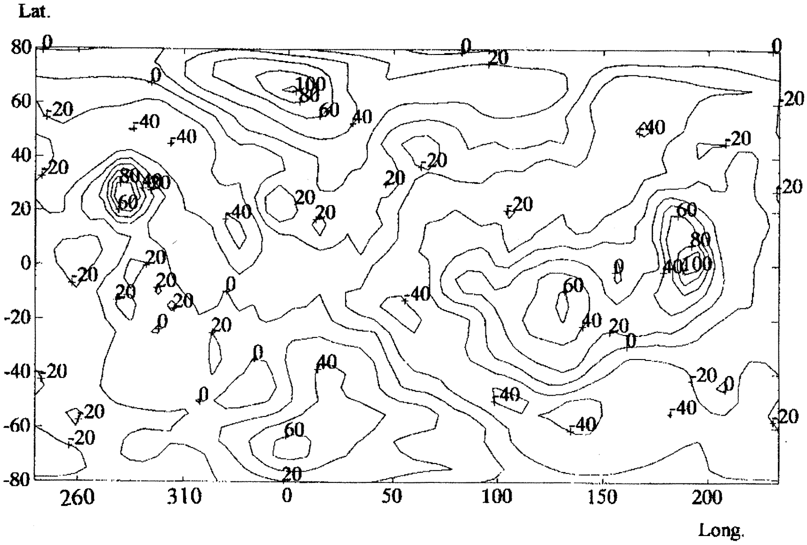

Figure 2. Geoid heights in metres, based mainly on the elliptic orbit of Magellan, but incorporating some of the tracking of the circularized orbit (Konopliv *et al.* 1993).

figures 1 and 2, most striking are the high correlation of gravity with topographic elevation and the high ratio of correlated gravity to elevation, about four times Earth's. While the gravity field over the plains is rather mild, the highs over the volcanic features Atla and Beta are 40% greater than the maximum on Earth (over Indonesia). More moderate highs occur over the features thought to be convergent, Ovda and Thetis and over Ishtar, still debated as to cause.

3. Imagery

Radar imagery of 110 m along-track resolution now exists for more than 95% of the surface.

Probably the most important finding from imagery is that the distribution of 914 exogenic craters over the entire surface is close to random, with a moderately lower peak and broader distribution than purely Poisson. Taking into account the size of bolide that can penetrate the atmosphere, their spatial frequency – about two per 10^6 km^2 – implies an age of about 500 Ma (Phillips *et al.* 1992; Schaber *et al.* 1992). Furthermore, the larger craters have depth–diameter ratios that are generally greater than on Earth; more like those on Mars (Schaber *et al.* 1992). These ratios imply that the outer 100 km or more of Venus is quite stiff (Grimm & Solomon 1988), confirming the evidence from the gravity–topography admittance ratio.

The surface of Venus is marked by a wide variety of features of endogenic origin, described in detail by Solomon *et al.* (1992), Head *et al.* (1992), and other papers in the Magellan issues of the *J. geophys. Res.* (1992 August and October). Reference should be made to these issues for imagery details, since space limitations preclude their reproduction here. While sequences can be inferred (Kaula *et al.* 1992), the absolute ages of features are quite uncertain, and the sparsity of craters makes it possible that significant parts of the surface are well over 1000 Ma old. Over the plains dominating the surface, deformation from past activity is evidenced by distributed moderate strain, with sets of faults and folds, spaced a few to a few tens of kilometres apart (figure 3). Areas of more intense activity, comparable to mountainous areas on Earth, are limited to less than 10% of the surface. Some of these regions are dominantly tectonic in character, with much faulting and folding, while others are volcanic, with flow features and rifting. Most enigmatic is the highest area, Ishtar, which evidences both volcanic and tectonic features within a few hundred kilometres. Some feature types are peculiar to Venus. *Tesserae* are regions of intense faulting and folding about two or more directions. *Coronae* are quasi-circular structures with surrounding rims and trenches and appreciable volcanism, too irregular to be collapsed impact craters. Coronae are usually a few hundred kilometres in diameter, but one, Artemis, is 1800 km. The trench around Artemis is asymmetric, like subduction zones in Earth. *Chasmata* are straight troughs hundreds of kilometres in length and 10–100 km wide. Two measure 7 km from adjacent ridge to the bottom, and are asymmetric, like subduction trenches: Diana and Dali chasmata, between Thetis and Atla. Also peculiar to Venus are *canali*: channels some hundreds of kilometres long. Typically these channels are 1–3 km wide, but they include a variety of wider and more complex forms.

The imagery also evidences many wind effects: most of them associated with topographic obstacles, but some with large impacts. But the high-resolution imagery confirmed that erosion and sedimentation on Venus are quantitatively negligible (Arvidson *et al.* 1992), so that tectonic and volcanic effects are preserved for several hundred million years. Hence there are many overlays of features generated in greatly different epochs.

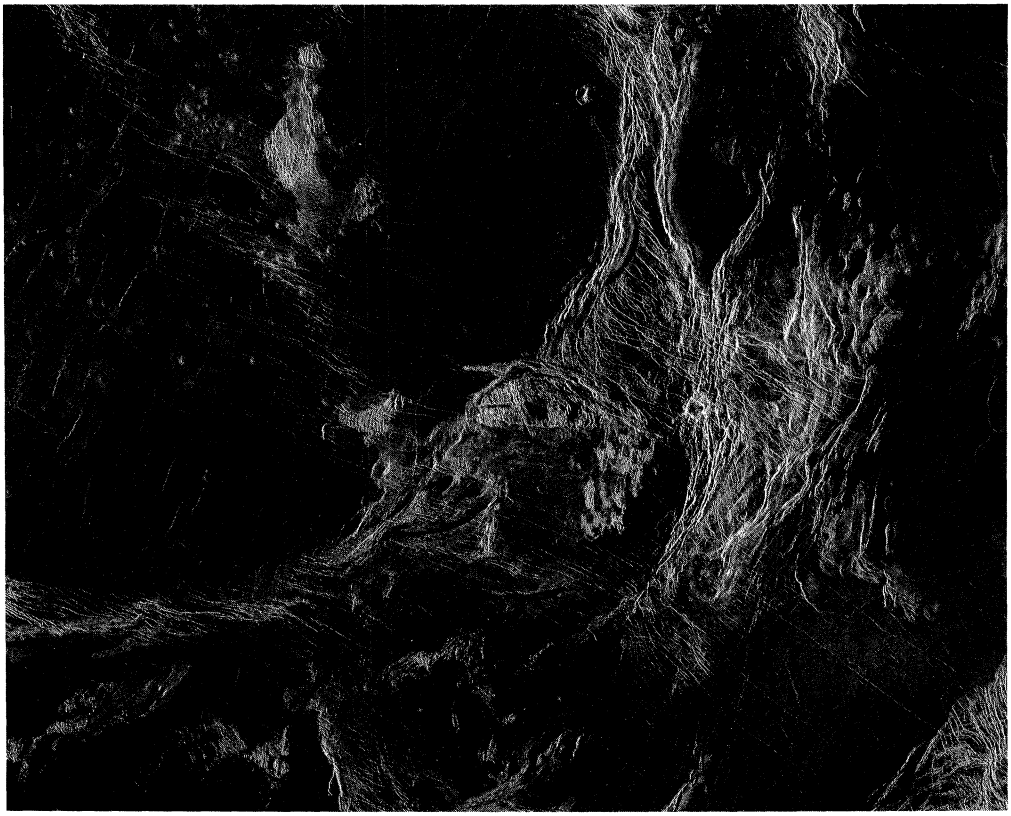

Figure 3. Typical plains tectonics, centred at 45 S, 347.3 E; about 500 km × 500 km. Note the multiple trends. The relief in this area is less than 600 m.

4. Interpretation

Venus is simpler than Earth: it lacks a satellite, magnetosphere, ocean, and biosphere, and probably lacks an asthenosphere and a solid inner core. The main reason for most of these lacks is that Venus is hotter: sometimes a direct effect (e.g. the lack of an ocean), sometimes an indirect (e.g. the lack of a magnetosphere). A remarkable number of the differences of Venus from Earth can be explained as arising from its evolution, with only minor nudges in the beginning.

The amount of carbon dioxide in Venus's atmosphere is about the same as in Earth's atmosphere + crust + ocean, within a factor of two (Walker 1977). A greater problem is the mantle content of CO_2 for both planets. A consequence of Venus's atmospheric CO_2 is a much higher surface temperature of about 740 K. Any water from the interior or impacts is vaporized – to be circulated to the top of the atmosphere, where it is photodissociated. The hydrogen released by this dissociation is evaporated to space, while the oxygen is recirculated to be combined with the rocky surface (Prinn & Fegley 1987). Also suggesting appreciable mantle volatiles is the sporadicity of upper atmosphere SO_2, which, if real, would require large-scale pyroclastic volcanism.

The many channels found in the Magellan imagery suggest abundant material of low melting temperature, such as carbonates and sulphides (Baker *et al.* 1992). Hence there may be a lot more CO_2 in the upper mantle of Venus. The low solubility of CO_2 in magmas leads to it having little effect on petrological differentiation (Hess & Head 1990), so the crustal evolution of Venus would be like the Moon's: quite dry, but still allowing secondary differentiations.

The similar K/U ratios of Earth and Venus are significant because the two elements are very similar in behaviour in a solid planet, so that equal K/U ratios imply equal bulk abundances of potassium. Equal potassium K implies generation of equal amounts of radiogenic argon, ^{40}Ar, in the two planets. Hence the lower abundance in Venus of atmospheric ^{40}Ar must be attributed to a lower efficiency of outgassing. This lower efficiency is easily explained by a much lower rate of erosion. Hence the higher abundance of primordial argon, $^{36+38}$Ar, in Venus's atmosphere cannot be attributed to a greater efficiency of outgassing in its history; it must be a residue of the original inventory of volatiles in the planet.

The high surface temperature of Venus has important consequences for the interior of Venus through the lack of oceans and the negligible erosion. Apparently related to the latter is the high ratio of correlated gravity to topography, which implies a great depth of effective compensation for Venus's topography – an average of 140 km for wavelengths longer than 2000 km. This great depth suggests support by mantle convection, which in turn requires that there cannot be a shallow weak layer like the asthenosphere under Earth's oceans (Phillips 1990). The most plausible explanation for this greater stiffness of Venus's upper mantle is that it is very dry: no water is recycled to it because there is no ocean on Venus (Kaula 1990*a*). However, to deliver the same heat flux, a dry mantle would probably heat up until its viscosity was as low as a wet mantle's. Hence there is plausibly a greater concentration of radioactive heat sources in Venus's crust, which would act to raise the effective viscosity through lower temperatures and lower strain rates. Thus the effect of Venus's dryness is to inhibit recycling of heat sources both through the stiffer rheology and negligible erosion of secondary differentiates.

The persistence of the depth–diameter ratios of large craters requires appreciable strength at depths to about 100 km. Previously these high ratios were thought to limit the thickness of crust on Venus because it would deform easily (Grimm & Solomon 1988). But now the new rheology of dry diabase by Mackwell *et al.* (1993) indicates that it is almost as strong as dunite. The Earth's crust now is a minor part that has not been recycled by subduction – mostly of oceanic crust, but also of eroded continental crust. If Venus lacks a similarly efficient mechanism of recycling, then it should have a much thicker crust, perhaps reaching the basalt–eclogite phase transition, about 80 km deep.

The higher surface temperature is probably felt by the interior of Venus all the way to its core. But at Venus's centre the pressure is less than at the boundary between the inner and outer cores of the Earth. Hence, given similar compositions (as implied by the similar reduced mean densities), the solidification of an inner core is *not* occurring in Venus. Solidification of the inner core is believed to be the energy source for the geodynamo that is the source of the Earth's magnetic field. Hence Venus's lack of a magnetic field and thus a magnetosphere is plausibly caused by its lack of a solid inner core (Stevenson *et al.* 1983).

Only two differences of Venus from Earth depend on origin circumstances: (1) the high abundances of inert gases – e.g. a ratio of about 80 in $^{36+38}$Ar; and (2) the slow retrograde spin. These differences are both plausibly the consequence of a terminal phase of formation with very few big bodies, leading to large chance variations: the biggest body to hit Earth could have been much more massive than the biggest to hit Venus. Hence the heating of Earth would have been much greater than that of Venus, leading to a much greater loss of volatiles (Cameron 1983). There also would have been differences in the direction and offsets of the few biggest impacts, causing differences in the spin rates and directions (Kaula 1990*b*). A retrograde spin of any obliquity is driven toward a 180° obliquity by tidal friction. A collision into the early Earth great enough to create the Moon would have removed any atmosphere, but would have left some volatiles in the mantle. The progression in energy of impacts indicates that most entrained volatiles were acquired quite early (Zahnle *et al.* 1988; Ahrens 1991). The retention of inert gases by Venus implies that it also acquired a lot more active volatiles, particularly H_2O and CO_2. To dispose of the solar complement of H_2O to Venus's $^{36+38}$Ar, a strong discriminant between water and argon is needed. One discriminant is that after photodissociation of water, the hydrogen atoms are much lighter than the argon: if the early Sun was vigorous enough, the hydrogen would have been blasted off hydrodynamically, but not the argon (Kasting *et al.* 1984). Another is that water is more soluble in magma than argon by a factor of about 700, which suggests that the missing water is buried deep in Venus's mantle (Zhang & Zindler 1988). But there are not the same discriminants between argon and carbon dioxide, and there plausibly should be much more CO_2 in Venus than the equivalent of the Earth's ocean plus crustal content now in Venus's atmosphere.

5. Conclusions

The major differences of Venus tectonics from Earth tectonics found by Pioneer Venus – the high gravity–topography correlation and admittance ratio and the absence of a spreading ridge system – were early recognized as possibly explicable by Venus being moribund – more like the Moon than Earth, despite being much larger. But wishful thinking induced many attempts to explain Venus's features either as due to processes like those on Earth – plate tectonics and its sustaining mantle convection – or as due to ongoing convection and tectonics of a more regional character. When the abundance and random location of large impact craters became apparent, further wishful thinking induced the idea that Venus is temporarily quiescent, at a low in an episodic behaviour. The models that have been presented to support this hypothesis (Turcotte 1993) have been much simpler than an actual three-dimensional planet with a strongly temperature and stress dependent rheology. What seems more likely is that Venus has a net upward differentiation of heat sources much greater than Earth's. The lack of water certainly prevents the erosion of secondary differentiates, important in recycling heat sources to the Earth's mantle, and probably inhibits recycling through making the rheology of both crustal and mantle rocks much stiffer. The recent dry diabase experiments by Mackwell *et al.* (1993) are an important complement to the dry dunite experiments by Karato *et al.* (1986).

There remain as problems the few features suggestive of ongoing tectonics through their high gravity: topography ratios (Beta, Atla) or marked topography involving steep slopes (Artemis trough, Diana and Dali chasmata, Maxwell Montes). Venus (like Mars) cannot be entirely dead. But the terminal tectonic activity of a planet must be complicated, caused by density and heat source inhomogeneities heavily dependent on earlier activity. The Earth is the peculiar planet, mainly because of its water.

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Discussion

T. Owen (*Institute for Astronomy, University of Hawaii, U.S.A.*). It is not enough to have a larger icy impact on Venus than on Earth to explain the large primordial argon abundance in the Venus atmosphere. The reason is that Ar/Kr in Venus is distinctly different (more solar in character) from that on Earth. Hence you must have an icy impactor with a different composition. We have suggested a low-temperature ($\leqslant 30$ K) icy planetesimal, but to check this, we need to know the xenon abundance and xenon isotopes on Venus. It is highly desirable to include a suitably equipped mass spectrometer on any further Venus probe mission to make this measurement.

W. M. Kaula. It has been bothersome that the krypton ratio of Venus to Earth is so much less than the argon ratio. I was not aware of the measurements of inert gas adsorption at low temperatures. That the largest icy planetesimal impact was much bigger than the second largest is plausible; also plausible is that it was much smaller than the largest rocky planetesimal impact, because of the screening effect of Jupiter. Yet to be solved is how big a high-velocity impact ratio into Venus can add volatiles rather than eroding the atmosphere.

S. K. Runcorn. It is important to emphasize the similarity of the fundamental processes in the interiors of the terrestrial planets and the solid satellites of the major planets. The fundamental physical process is the same: the outward transport of heat through convection by solid state creep in the interior and the escape of heat by molecular conduction through the boundary layer. The surface manifestations of convection depend critically upon the boundary layer – in terrestrial bodies, the lithosphere. Their nature can be qualitatively very diverse, depending on the thickness and rheological properties of the lithosphere, which are a function of temperature, the time scale of the stress, and composition – especially the water content. The primary consequence of solid state convection is low harmonic departure of the gravitational field from the hydrostatic model.

Plate tectonics on the Earth, the grid system on the Moon, sulphur volcanism on Io and the fascinating revelations about the surface of Venus should be viewed as secondary!

W. M. Kaula. We all certainly agree that the physical fundamentals of heat transfer in the solid Solar System bodies are the same. But the boundary layer nonlinearities mentioned above should differ significantly between icy and rocky bodies, and the degree to which thermal and compositional evolution has advanced varies inversely with size of the body – except for Io, which has its peculiar tidal energy source.

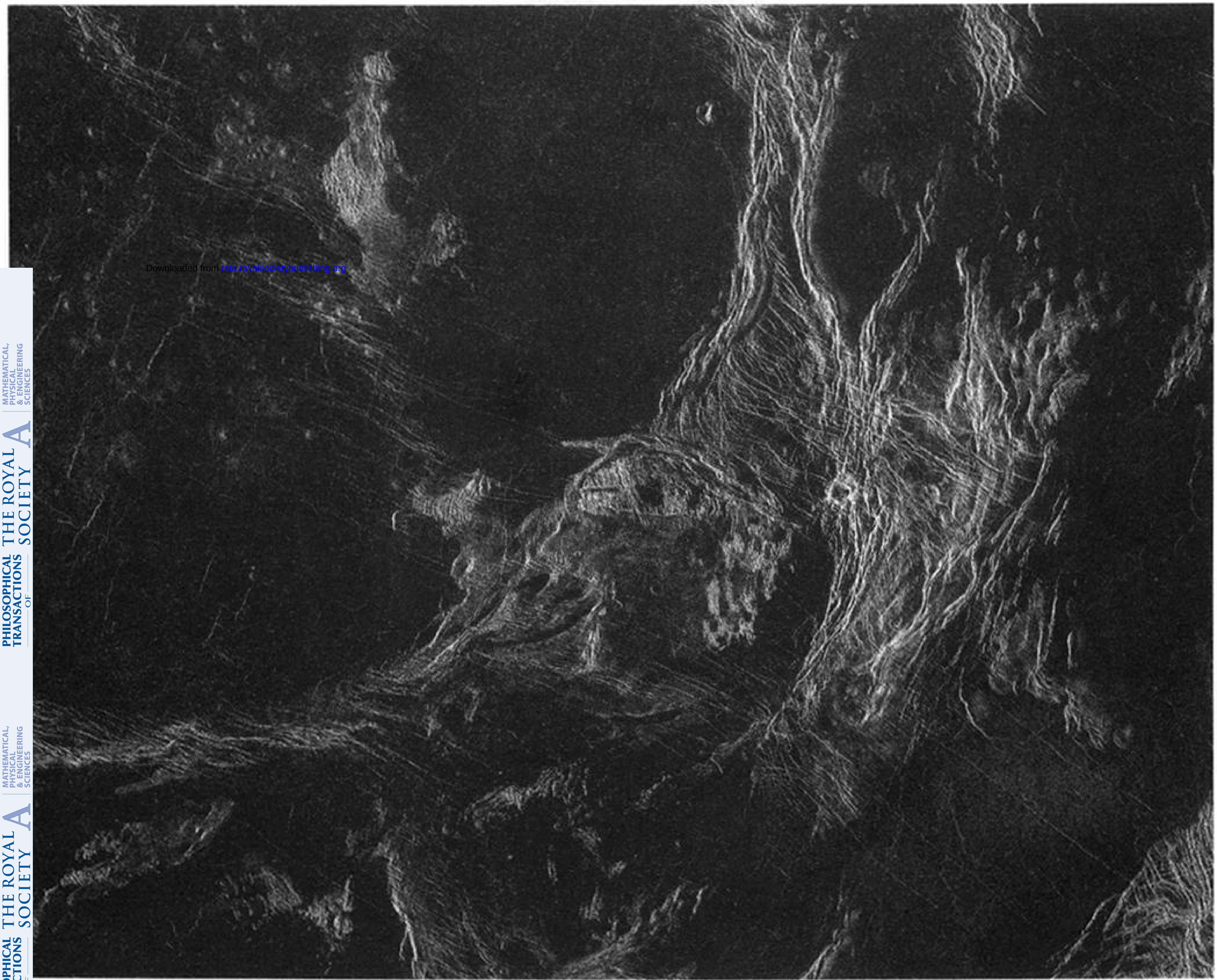
D. C. Tozer (*Department of Physics, University of Newcastle upon Tyne, U.K.*). Professor Kaula's remarks about the relatively greater 'stiffness' of the Venusian outer layers compared with those of the Earth is made particularly significant in view of the known higher surface temperatures of Venus. The really important consequence of the Venusian observations is the implications it has for thinking about what phases are controlling the temperature dependence of Earth's mantle rheology. The conventional view (not mine) has been that Earth's mantle rheology is essentially the same as the mineral olivine – in effect determined by the most creep-resistant phase one can expect to find in terrestrial planet mantles in any quantity. Given the Venusian situation, I think one is forced to conclude that Earth's mantle rheology cannot be controlled in its most refractory phases. I will merely reiterate what I have said many times before: this can only mean that horizontally averaged temperatures in Earth's upper mantle are many hundreds of degrees less than what is conventionally believed on the evidence of magma temperatures – magma only rises to the surface because its temperature and the consequent rheological state is so untypical of horizontally averaged conditions.

W. M. Kaula. I am not sure what Dr Tozer is driving at. Certainly, modellers who assume viscosity to be a function of radius only do so because of computer limitations. It is also consensus that heat flow data make it unavoidable that there be lateral temperature variations of hundreds of degrees only 100 km or so deep in the Earth, which must greatly affect viscosity. Temperature variations associated with magmatism are even higher, but more limited in extent. But on the broad averaging scales of thousands of kilometres and millions of years, the fundamental factor is the amount of heat removed from a planet: a drier body will warm up to flow enough to maintain a rough steady state ('how rough' is debatable). Mainly for this reason, I conjecture that the 'stiffness' of Venus's upper mantle requires that it has upwardly differentiated its heat sources much more than has Earth. The inhibition of crustal recycling implied thereby involves different considerations, such as the role of water in erosion and subduction.

D. C. Tozer *(Added in proof)*. I am pleased to see Dr Kaula also believes there may be large lateral temperature inhomogeneity in deep terrestrial planet interiors, though I believe he greatly overestimates what can be inferred about it from surface heat flow observations. I will only say that for decades I have encountered criticism bordering on ridicule of my confident prediction that magma temperatures are many hundreds of degrees above the average value at their depth of origin.

One's attitude to such inhomogeneity and views on the cause of Venus/Earth differences are strongly conditioned by the way planetary material rheology is represented in planetary heat transfer problems. Modellers who make viscosity a function of radius not only remove any possibility of predicting large lateral temperature differences but are also missing the essential point that viscosity values both control, and are controlled by, the heat transport process. This is but one example of a reflexivity that has made a modern understanding of that process quite unlike previous ones based on heat conduction theory. For example, because an upward differentiation of radiogenic heat sources requires a convective process to facilitate it, one can show that it alone will not lead to any significant change in horizontally averaged deep planetary temperatures. Such behaviour is relevant to the question of interpreting the apparently greater 'stiffness' of Venus's outer layers. Rather inconsistently with his previous reply to Professor Runcorn, Dr Kaula may propose a thicker, more extensive, buoyant crust to explain the present absence of plate tectonic movements on Venus, but I do not see how this begins to explain the 'stiffness' difference. One needs a compositional difference that, in rheological terms, more than compensates for the evident temperature difference of the two crusts – my original point. I think we may agree this difference is most readily attributable to water having been able to remain a major factor facilitating Earth's crustal movements. His invocation of a lack of crustal recycling I see as a consequence rather than a cause of a most interesting difference between the two planets.

As a general comment on the value of space probes to other planets, it would be hard to imagine a better way of answering fundamental questions about the workings of our own planet than the study of another planet so similar and yet so different as Venus.



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