Venus: A Contrast in Evolution to Earth

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Of the planets, Venus and Earth are by far the most similar in primary properties, yet they differ markedly in secondary properties. A great impact into Earth is believed to have created its moon and removed its atmosphere; the lack of such an impact into Venus apparently led to a greatly differing atmospheric evolution. The lack of an ocean on Venus prevents the recycling of volatiles and inhibits subduction, so that its crust is probably more voluminous than Earth's, although distorted and quite variable in thickness. Venus's upper mantle appears to be depleted in both volatiles and energy sources because, in addition to the lack of volatile recycling, melts of mantle rocks are more dense than their solid matrix at pressures above 8 gigapascals and hence sink if they occur at depths below 250 kilometers. Appreciable energy sources persist at great depths to sustain the few great mountain complexes. The greatest current problem is reconciling the likelihood of a voluminous crust with indications of considerable strength at shallow depths of 20 to 100 kilometers.

VENUS DIFFERS FROM EARTH BY ONLY 18.5% IN MASS AND 2% in mean density reduced to the same pressure (Table 1). All other bodies in the solar system differ from Earth by more than 89% and 8%, respectively, in these primary quantities. The closeness in reduced density, together with the limited number of abundant elements that constitute the bulk of planets, means that Earth and Venus must have similar oxidation levels and iron and silicate contents.

The National Aeronautics and Space Administration (NASA) partly justifies the exploration of the planets as helping to understand Earth. Because of the great differences in secondary properties (many that are qualitative, as well as the quantitative differences in Table 1) arising from similar primary properties, caution must be exercised in drawing analogies from Earth about other planets, or the converse, and more resort made to the underlying physics and chemistry. Hence hypotheses developed to account for characteristics of Earth in many cases should lead to quite different interpretations when adapted to Venus.

In this article, I summarize the leading data about Venus and current interpretations thereof and then attempt to explain discordances among these interpretations as consequences of Venus's evolution. Although the subject is Venus, the ideas used were largely developed for application to Earth, whose evolution continues to receive more study because there persist significant uncertainties about such major features as the pattern of mantle convection (*1*). The conjectures in this article are quite speculative and inconclusive because data about Venus are confined to what can be obtained from orbiters and short-lived landers. It is expected that the Magellan spacecraft, now on its way to Venus, will obtain imagery, altimetry, and gravimetry more detailed and extensive than has been available heretofore. These data will settle some of the conjectures advanced here and elsewhere but will doubtless give rise to many new surprises.

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Atmosphere

The most obvious marked difference between Venus and Earth is the presence on Venus of a thick atmosphere in chemical equilibrium that drives the surface temperature up to 730 K. In contrast, Earth has an ocean and a disequilibrium atmosphere. The atmosphere of Venus is only 95 ppm of its mass. But it constitutes a hot insulating layer that greatly affects the long-term evolution of the bulk of Venus because it prevents recycling of volatiles and raises the temperature throughout the interior. A plausible result of these higher temperatures is the lack of a magnetic field in Venus. The pressure at the center of the planet is less than at the boundary of Earth's inner core. Hence, as pointed out by Stevenson and colleagues, Venus cannot have the energy source widely believed to drive the geodynamo on Earth: solidification of this inner core (*2*). But much more important to the main themes of this article is the influence on the interior evolution of Earth of its hydrosphere, which through recycled hydrated rocks has major effects on rheology—the existence of an asthenosphere—and on petrology—the occurrence of volcanism over subduction zones.

Aside from their different magnetic fields, it is implausible that the great differences between Earth and Venus arose from their bulk characters. Hence we must look to differing evolutions arising from different circumstances of origin. The key matter of a surface temperature sufficient to allow water to condense on Earth, but not on Venus, could have evolved from a much smaller difference than the present 450°C: a difference as small as the 49°C difference in equilibrium blackbody temperature would have been sufficient. Earth's complement of Venus's atmospheric CO_2 could be in carbonate rocks and the mantle, whereas Venus's complement of Earth's surface H_2O is generally thought to have been photodissociated, so that the H^+ was lost to space and the O_2 was fixed in rocks. However, the D:H ratio on Venus is much higher than on Earth; this difference led Donahue and colleagues to infer that a water layer on Venus could have been only a few meters deep (*3*). But subsequent workers have conjectured that there was a massive early hydrodynamic loss (*4*); that there have been significant cometary inputs of water (*5*); that water was never acquired by Venus in the first place (*6*); and that not much water has been outgassed from solid Venus, but that it has remained in the interior (*7*). It is difficult to understand why the hydrodynamic loss did not comparably affect the inert gases; why the cometary flux was so much greater in the past; or how subsequent dynamical mixing did not obliterate much of any nebula-generated differences. Hence the most plausible hypothesis is that of Zhang and Zindler: the water remains in the interior (7). This high content of interior H_2O leads to difficulties discussed below.

Origin

Only two differences between Venus and Earth must be consequences of planetary formation:

1) Earth has a large moon and a rapid prograde rotation. Venus rotates slowly retrograde, so that any satellite would have long since spun in from tidal friction (*8*).

2) Venus has a much greater abundance of nonradiogenic inert gases; in particular, it has about 80 times as much atmospheric $^{36+38}$Ar as Earth (*9*).

These two primordial differences are plausibly outcomes of gravitational interactions and collisions among very large planetesimals in the terminal stage of formation of the terrestrial planets, as modeled by Wetherill (*10*). In this process, Earth apparently chanced to be hit by a very large body, perhaps Mars-sized, while the greatest impact on Venus was appreciably smaller. Monte Carlo models of the late stages of terrestrial planet formation produce such differences in a minor, but not insignificant, number of cases (*11*). The main stimulus for the current general acceptance of the great impact model is that it accounts for leading properties of the moon: its orbit, size, and low contents of Fe and volatiles (*12*). But the giant impact also seems the only plausible explanation for the great difference in the concentrations of primordial inert gases between the atmospheres of Earth and Venus, as first suggested by Cameron (*13*). In the penultimate phase of terrestrial planet growth, dynamical interaction among planetesimals would have led to appreciable interzone mixing of composition, including volatiles. This homogenization of protoplanetary material would have led to similar volatile contents in Earth and Venus, if there were not loss in one of them by great impact. Dynamical mixing also makes implausible models that hypothesize solar effects on the nebula to explain marked differences, such as that Venus never acquired much water (*6*).

Many difficulties remain in models of giant impacts currently being computed by Benz and colleagues (*14*). The collision process is far from a solely mechanical phenomenon. The primordial atmosphere could not have been removed by the impact itself, because most of the energy is absorbed in the vaporization of condensed matter, and the initial shock wave actually drives the atmosphere back into the planet (*15*). Rather, the raising of temperatures by a few thousand kelvin leads to a "planetary wind" that drives off the volatiles. The removal of the primordial atmosphere of Earth plausibly allowed it to cool sufficiently to allow the oceans to rain out, perhaps the most critical step in allowing Earth to have a different evolution from Venus.

Although some consequences of a great impact are uncertain, its occurrence is quite plausible and definitely not ad hoc. Quite the contrary: current models of formation of terrestrial planets by merger of dynamically interacting planetesimals, starting from an initial population of many small bodies, lead to a final phase of large bodies among which no one outstrips the others in mass by more than a factor of 10 or so (*10*). Hence large stochastic variations, such as hypothesized to account for lunar properties and Earth:Venus differences, are quite plausible. In precomputer days, tidal disruptions and runaway growths were suggested as mechanisms that could lead to one dominant body in each zone (*16*). But the former neglected planetesimal viscosity, and computer simulations indicate the latter to be an unreached asymptotic state.

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 plus ocean constituents†	H_2O	$\log_{10}$(kg/kg)	−3.6	<−10.0
	CO_2	$\log_{10}$(kg/kg)	−7.5	−4.0
	N_2	$\log_{10}$(kg/kg)	−5.6	−5.6
	^{36}Ar	$\log_{10}$(kg/kg)	−10.5	−8.6
	^{40}Ar	$\log_{10}$(kg/kg)	−7.9	−8.5
K:U ratio			10^4	10^4
Magnetic moment		tesla-m^3	7.5×10^{15}	$<3 \times 10^{11}$

*Corrected to a mean pressure of 10^9 Pa, on the assumption that all Fe and FeS are in a central core. †Masses in proportion to planet mass.

Evolution

If Venus has retained much more of its primordial inert gases than Earth, then it likely has retained much more water than Earth, because water is much more easily bound within condensed matter, either as a solute or as a hydrating component. The most important of these differences is the solubility, since outgassing is dominantly auxiliary to volcanism. In particular, H_2O is much more soluble in magmas than other volatiles: 100 times as much as CO_2 and 700 times as much as argon (*7*). Hence it is plausible that a much larger fraction of Venus's primordial argon outgassed than of its water, thus leaving appreciable water in Venus's interior. Outgassing of $^{36+38}$Ar must have occurred very early, probably concurrent with planetesimal impacts, because Venus's atmosphere has only one-third as much radiogenic ^{40}Ar as Earth's atmosphere, despite a similar K:U ratio (*17*). The low abundance of ^{40}Ar also implies that it has been more difficult for volatiles to rise to the surface of Venus than to the surface of Earth since early in their history, because the half-life of ^{40}K is 1.47 billion years, before which half the ^{40}Ar would have been generated.

On Earth, nearly all outgassing is by volcanism at mid-ocean rises (outgassing at these sites is facilitated because the ocean rise and floor are part of the mantle convective system). This convective system is extraordinarily effective at recycling oceanic crust in subduction zones, including hydrated crust, and thus volatiles. The mean life at the surface of oceanic crust is 100 million years (*18*), less than 3% of the age of Earth. The total volume of continental crust is only 3.5 times that of oceanic crust. Therefore, the accumulation of continental crust over Earth history incorporates only a minor part of the material brought up at the ocean rises and carried over to subduction zones: less than 20%, if allowance is made for recycling of continental material (*19*).

If convective recycling of crust in Venus were only moderately less effective than in Earth, because of dryness arising from the lack of an ocean and thinness of the lithosphere arising from the high temperatures, the entire surface would plausibly have become choked by crustal material (*20*). If this low-density crust could have maintained its integrity as a relatively uniform layer, it would have been a considerable barrier to mantle convection reaching the surface, and thence to plate tectonics. However, as discussed below, it is unlikely that this integrity has persisted. In any case, most important is the lack of volatile recycling.

If crustal creation always occurred on Venus at the same rate as on Earth (currently about 18 km^3 per year) and there were no recycling of crust, the crust now would be well over 100 km thick. However, at pressures of 1.5 to 2.0 GPa, basalt (or gabbro) undergoes a phase transition to eclogite, which is denser than the ferromagnesian rocks expected to constitute the mantle. This transition would thus limit the mean crustal thickness to something less than 100 km, dependent on temperature (*21*). This "delamination" process would act to recycle crustal material to the mantle. This recycling in Venus would be much more complex than subduction in Earth, because of the absence of volatiles and the fracturing of crust. It would be very much enmeshed in downflows of mantle convection more intricate than instabilities of oceanic lithosphere on Earth. The most evident locus of such processes is the Ishtar plateau, but this is quite speculative.

Geology

Venus differs from Earth in having a single mode of elevation (Fig. 1), with the high elevations limited to three plateaus (*22*). About 60% of the surface of Venus has been mapped by radar imagery, with a variation in resolution from about 1 to 20 km. This imagery is the principal means of geologic interpretation (*23*). The main inference is that about 75% of the planet's surface is volcanic and 25% is tectonic. The distinction between "tectonic" and "volcanic" areas is that the tectonic areas have undergone significant distortions since they were formed by solidification of the lava flows. On a small scale, radar reflection characteristics indicate that most of the surface is hard rock and that less than 20% is "soil-like" in character. The volcanism is almost entirely of the shield type: lava flows of gentle slope, indicating low viscosity and low water content. The average age of these flows in the northernmost 25% of the planet is estimated to be 1 billion years (from crater counts); some lower ages are estimated for the less well-imaged surface at lower latitudes. The composition of the crust by reflection spectrometry at Venera landing sites, in low-latitude rolling plains, is similar to that of Earth basalts; the main difference is that the crust on Venus has a slightly higher MgO content (*24*), which is suggestive of greater partial melting. The amount of erosion and sedimentation (most likely eolian) is slight: a rate of resurfacing less than a few centimeters per million years has been estimated from halos of debris around impact craters (*23*).

A variety of tectonic forms have been inferred from the high-resolution Venera 15 and 16 imagery north of latitude 30° (*23*). Some of the most distinctive forms are the following:

1) Tesserae: densely packed ridges and grooves that intersect each other at various angles. They are located in upland areas, have crest-to-crest spacings of 5 to 20 km, and have trough-to-ridge heights of a few hundred meters.

2) Ridge-and-groove belts: nearly parallel ridges, also with spacings of 5 to 20 km and heights of a few hundred meters. Some are located in upland areas, others in lowland. The lowland belts occur at spacings of 300 to 500 km.

3) Coronae: concentric rings of ridges and grooves, with spacings of 5 to 20 km and diameters of 50 to 600 km. The coronae show varying degrees of radial as well as concentric structure and are higher than the surrounding plains.

4) Rift zones: the broad updoming of Beta Regio contains linear depressions several hundred kilometers wide, within which are multiple faults spaced 5 to 20 km apart. Some of these rifts are more than 1 km deep.

5) Mountain belts: regions around Ishtar characterized by features similar to those in zones of convergence on Earth. Deformation ranges from simple rise, foredeep, and scarp geometries (see Fig. 2) to complex folding and faulting.

The largest region of high elevation, Aphrodite, falls along the equator, in an area where only low-resolution imagery is currently available. Head and Crumpler have identified in its western part, stretching over some 7500 km, a ridge system from altimetry that has some similarities to spreading ocean rises (*25*), such as symmetries of topography about the crest extending 1500 km to each side; fracture zones at intervals of 500 to 1500 km, which offset the ridges by 100 to 1000 km; and elevation differences across fractures similar to those for lithosphere of different ages. Differences from Earth's ocean rise system include a much shorter length (*26*); a much greater range in crest elevation (*26*); nonconcentricity of fracture zones (*27*); and abrupt drops in elevation about 1000 km off the crest (*25*).

On Earth, the oceanic lithosphere is clearly the boundary layer of mantle convection. The elevation of the sea floor decreases at a rate

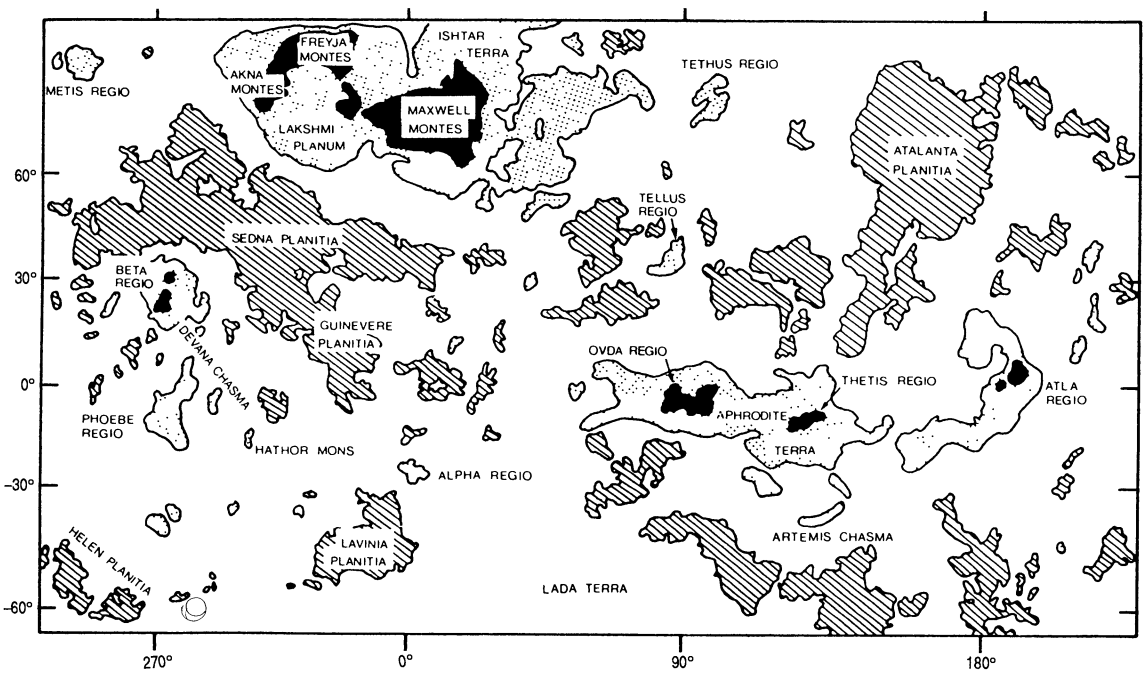

Fig. 1. Altimetry of Venus. Elevation ranges and customary designations: cross hatched: <0 km, lowlands; blank: 0 to 1 km, rolling plains; stippled: 1 to 3 km, uplands, black: >3 km, the highest regions. Elevations are with respect to a sphere of 6051-km radius.

proportional to $t^{1/2}$, where t is age, or time from the crest, because of conductive cooling of the translating lithosphere (*26*). If a feature similar to Earth's rise system existed on Venus, its crest would be about 1.4 km high, well above the error level of the Pioneer Venus altimetry. To analyze Venus altimetry from such rises, the $t^{1/2}$ shape must be replaced by an $s^{1/2}$ shape, where s is distance off the crest, because chronology is lacking on Venus. An analysis of heights proportional to $s^{1/2}$ can be tested on Earth, and then estimates of material and heat delivery on Venus made from altimetric maps of Venus's surface. Kaula and Phillips (*26*) carried out an analysis of this type and concluded that less than 15% of the heat flow from Venus could be by sea-floor spreading, in contrast to 70% on Earth.

This quantitative insufficiency of simple plate-tectonic models for Venus does not preclude horizontal motions of the surface, as suggested by symmetries in altimetry of Western Aphrodite (*25*) and distorted regions around Ishtar (*23*), nor does it preclude association of these motions with underlying convective flows. Indeed, it would be surprising if there were not crustal spreading in a planet that is quite hot and has energy sources sufficient to support the great plateaus of Aphrodite, Ishtar, and Beta Regio. Support of these elevations, kilometers high, by mantle convection would lead to severe shear in any surrounding crust more than a few kilometers thick (*28*). Hence, if there is a voluminous crust on Venus, then the relation of surface spreading to mantle convection will be much more complex than occurs under the oceans of Earth. In particular, there would be considerable variations from place to place in both crustal and lithospheric thickness, consequent upon the stresses imposed by the convective system that sustains the great plateaus.

Tectonics

The two scales of features in the imagery, 10 to 20 km and 300 to 500 km, in the tectonically distorted regions described above are suggestive of mechanical instability, either extensional or compressional, in a layered rheology, with two layers of strength sandwiching a weak layer. The most direct inference from analogous features on Earth is that there is a 30-km crust in a 100-km lithosphere. In this model, the narrow spacing arises from a weak zone in a warm lower crust, and the wide spacing from an asthenosphere below the

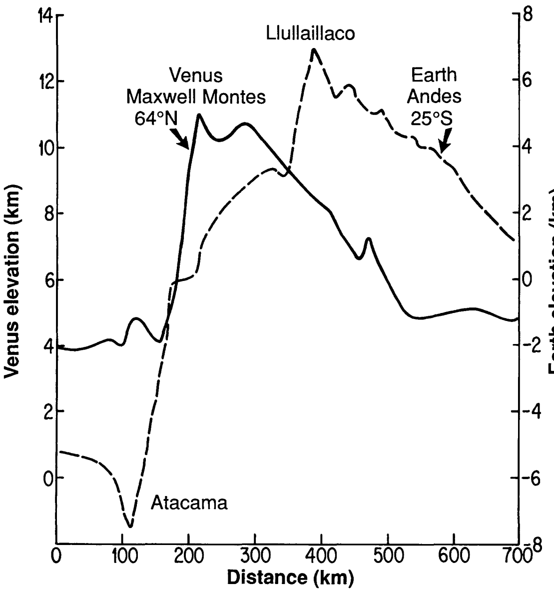

Fig. 2. Topographic cross sections of Maxwell Montes on Venus at 64°N and the Andes on Earth at 25°S at the same scale.

lithosphere (*29*). Such a thick lithosphere is difficult to reconcile with the warm state of Venus, because, if mantle convection is buried beneath a thick crust, it would be highly conducive to an asthenosphere, as discussed below. Rheological layering in the crust, as has been suggested for continents on Earth (*30*), is quite plausible. But experimentally all crustal rocks are so much weaker than ultramafic rocks (*31*) that in regions with appreciable stresses they may greatly obscure the pattern of mantle convection by deforming and flowing so as to pile up in low-stress regions, which tend to be at lower elevation. This effect would lead to a topographic range on Venus that is appreciably less than on Earth.

Time-evolutionary models of thick crusts over diverging and converging flows are needed to examine how the crust is deformed and flows over a mantle that has markedly higher viscosity and density than the lower crust. But such complicated models have only recently been developed for much better constrained problems on Earth (*32*). Venus may be more like Earth than it appears: the convective system may reach the surface in a few places, but, because of the difficulty of crustal subduction, in most places it may be concealed by piled up, old crust varying in thickness from 2 km to perhaps as much as the upper limit set by the basalt:eclogite transition, about 65 km. Certainly the tectonics of Venus is more like continental than oceanic tectonics of Earth.

The shorter wavelength features noted in the Venera imagery very likely do reflect mechanical instabilities in a layer of appreciable flexural rigidity 20 km or so thick. But it is less plausible that the longer wavelength features (>300 km) depend on the same mechanism. These features occur in settings where there plausibly could be convective effects: the lowland ridge and groove belts, roughly radial from Ishtar, and the coronae and rift zones, both suggestive of upwellings over plumes. More strongly demanding of a lithosphere several tens of kilometers thick are the craters analyzed by Grimm and Solomon (*33*), because their creation is exogenic. Their high depth:diameter ratio appears to require appreciable viscosities, limiting crustal thickness to 20 km or so. Nearly all these craters, however, are in the rolling plains surrounding the Ishtar Plateau.

The strongest evidence that the upper mantle of Venus has high viscosity comes from its gravity field and the relation of this gravity field to the topography. This relation is generally expressed as the "admittance ratio" of the gravity (or geoid) anomaly to the topography as a function of either geographic region or spherical harmonic wave number. Because of the limited strength of rocks, isostasy undoubtedly exists on Venus, as on any planet: surface highs and lows are compensated at depth by opposing lows and highs. Hence the main inference drawn from an admittance ratio is an apparent depth of compensation, or ADC. Analysis of Venus's gravity and the topography of the most prominent features yields a range of ADCs from 100 to 400 km, all much more than for suboceanic features on Earth (*34*). These prominences tend to dominate the harmonic ADCs in Table 2 (*35*); conditions could differ under the intervening gentle plains. But the main implication of the deep ADCs on Venus is that there cannot be an asthenosphere—a layer of weakness, as under Earth's oceans—because it would localize compensation to the upper zone of such a layer, as shown by the models of Phillips (*36*) and Kiefer and colleagues (*37*).

These data contradict the hypothesis of a thick crust shutting off mantle convection from the surface, because in the simplest model it would lead to a convective boundary layer at the top of the mantle and hence some tens of kilometers of superadiabatic gradient, leading to temperatures approaching melting and thus a shallow asthenosphere. But the large ADCs do indicate that, to support the prominent features, there must be a strong coupling of mantle flow with crust and lithosphere. In these active regions, there probably are not clear layerings of crust and lithosphere.

Magmatism

The upper mantle viscosity indicated by the gravity and topography of Venus is high enough to require, given the high surface temperature, both a significant upward differentiation of heat sources (to lower temperature gradients) and an absence of volatiles. The absence of an ocean would keep surface volatiles from being recycled to the upper mantle, as evidently occurs in subduction zones on Earth. The problem is why volatiles have not risen from greater depths in Venus. The answer appears to be the "Stolper effect" (*38*): at pressures above 6 to 10 GPa (60 to 100 kbar, or 200 to 300 km deep), silicate liquids are more dense than their crystalline phases, because of greater compressibility as well as higher Fe:Mg ratio. Hence magmas occurring at depths greater than about 250 km will sink rather than rise, carrying with them volatiles and trace elements that normally partition to the liquid phase. The vertical length scale of any significant upper mantle flows would be greater than 300 km, probably at least 600 km. Hence material in the upper mantle could be dried out in this manner. The effect may be small, but it is unidirectional and has had 4.5 billion years to operate.

Magmatism is also relevant to another problem of Venus, the transfer of heat through the lithosphere and crust. If heat removal by sea-floor spreading is slight (*26*), an evident mechanism is heat pipes (*39*), which entail mechanical and thermal nonlinearities not yet well understood. If this heat is delivered to the surface by volcanism, it is estimated that a volcanic flux of about 200 km^3/year is required (*39*). This is contradicted by low rates inferred from sulfur chemistry and crater counts and morphology (*40*): less than 2 km^3/year of lava flows, appreciably less than Earth's. The crater data may be qualified as coming from a limited region, but not the sulfur. There probably are occasional volcanic outbursts, as evidenced by a unique transient appearance of SO_2 in the atmosphere (*41*). But the volcanism implied thereby is a minor contribution to the ongoing heat removal that must be taking place. Hence, either there must be (i) a termination of magma pipes as plutons or (ii) a dearth of upper mantle heat sources, or both. The first possibility is expected from a thick crust, whereas the second is expected from a dry upper mantle, since heat-producing large-ion lithophiles (LILs) would have been removed with the volatiles either upward (mainly early in Venus's evolution) or downward.

Mantle Convection

Downward migration of volatiles and heat-producing LILs would be expected to create a zone of low viscosity and high heat contents at depth: at least as deep as the phase transition to perovskite at 700 km, perhaps deeper. Evidence of such a zone of weakness in Venus comes from the gravity field. The long wavelength component of Venus's field not correlated with the topography (*42*) is markedly smaller in amplitude than the same component of Earth's field. This relative mildness indicates that the viscosity of Venus's lower mantle cannot maintain as great density irregularities as can Earth's. But this inference is not conclusive; lesser variability in the lower mantle of Venus would be expected from both lack of subduction and lower energy from the core.

In any case, some deep energy sources are needed to account for the confinement of large surface manifestations of mantle convection to a few features. If these energy sources are also material sources, then their volatiles must become trapped in sinking magmas while the upflows are still more than 200 to 300 km deep.

The absence of an asthenosphere on Venus may also account for the dearth of linear features like the Earth's ocean rises. In three-dimensional computer experiments of thermal convection in spherical shells with constant viscosity, Bercovici and colleagues (*43*) obtained upwellings that were cylindrical rather than linear in pattern. Hence on Earth the suboceanic asthenosphere may be more important to plate tectonics than the lithosphere, providing the extraordinary ability to transfer heat and matter laterally, to create the linear ocean rises.

Table 2. Comparison of Venus and Earth gravity data (*35, 42*).

Spherical harmonic degree ℓ	Apparent depth of compensation		Uncorrelated field stress implication, Venus/Earth
	Earth (km)	Venus (km)	
2	−340	125	0.50
3	−25	190	0.27
4	60	170	0.47
5	−40	210	0.58
6	60	205	0.46
7	60	180	0.55
8	35	145	0.76
9	40	140	1.00
10	55	150	1.74
11	40	110	1.05
12	0	110	1.03
13	50	95	1.31
14	35	130	1.42

Magellan Observables

It is expected that the NASA mission Magellan, which will arrive at Venus in August 1990, will obtain radar imagery and altimetry that by mid-1991 will cover all longitudes at latitudes north of about 70°S (except for two minor gaps). The basic imagery data set will have a pixel size of 75 m, but for budgetary reasons only 15% of it will be processed to usable form; global coverage will be compressed to 225 m. The altimetry will have an accuracy of a few meters. During the period 1991 to 1993 an improvement of the gravity field could be obtained, but NASA is not yet committed to this "extended mission." If the orbit is not changed, these gravity data would vary in resolution from about 250 km at latitude 15°N to about 1500 km at latitudes 75°N and 55°S. A much more desirable procedure would be to reduce the orbit to minimum sustainable altitude, which would make possible 200-km resolution from pole to pole.

These detailed data from Magellan will make possible a comprehensive global characterization of regions, settling questions about the global applicability of inferences from Venera and Arecibo data. The data may also lead to an elementary stratigraphy: the sequencing of volcanic, tectonic, and perhaps erosional events, with a crude, but constraining, chronology from impact craters.

The extension of coverage southward of 60°S is also important, given the quantitative problem of how the heat gets out. It would not be surprising to find another feature like Beta Regio near the south pole.

In the more detailed coverage, particularly pertinent to thermal evolution is the extent of volcanism in the low latitudes, especially in Aphrodite Terra. If these low-latitude data do not lead to an appreciably higher estimate of global rate of volcanism than 2 km/year (*40*), then we should expect to see widespread evidence of a thick crust conducive to plutonism, such as relatively small amplitude (a few hundred meters) topography, as already suggested by the coronae and other features in the Venera imagery.

In the major tectonic regions, such as Ishtar and Aphrodite, detailed imagery should be examined for fracture patterns, to estimate the pattern of stresses occurring on the flanks of up- and downflows. Such analyses should eventually lead to better estimates of crustal volume, because the great differences in viscosity (*31*) would lead to significant variations in fracture and fold patterns.

These analyses will require appreciable advances in the modeling of tectonic phenomena and hence will take time. But, once they are accomplished, a much more refined estimate of global motion, and hence heat loss, can be made that takes into account the differences of tectonics on Venus from the simple oceanic tectonics on Earth, as well as a much improved chronology from impact craters.

Conclusions

The most remarkable characteristic of the Venus interior is that the upper mantle is so stiff, given that the planet is so hot. The instinctive reaction is to model the features evidencing this stiffness as if they were similar to relatively rigid crust-within-lithosphere features on Earth. These modelings leave begging the global questions of heat loss and crustal recycling. The heat flow from the mantle is plausibly less than on Earth, perhaps half as much. But it is still appreciable, and the heat must get out by means more effective than conduction or heat pipes through a layer of 100 km or so: it is surprising that there is only one Beta Regio, the best instance of a strong doming in the stiff matter of Venus's upper mantle. The crustal recycling is a more difficult problem, if there are not major features that are piling up sufficient crust to make possible operation of the basalt-eclogite transition.

It was evident from the Pioneer Venus altimetry a decade ago that Venus does not have ocean spreading and subduction like Earth, and that the convective sources necessary to support the few major features must be deep. It now seems clear that the stiffness of the upper mantle results from a combination of no oceans and the Stolper effect. But the higher resolution Arecibo and Venera 15 and 16 data, which indicate appreciable strength, have made a vexed question of crustal disposition. Is the crust nonuniform in thickness and greatly distorted, or is it recycled almost as effectively as Earth's crust by mechanisms not yet identified? At present, it is hard to predict how the Magellan data will help answer this central question.

REFERENCES AND NOTES

1. P. J. Wyllie, *Rev. Geophys.* **26**, 370 (1988).
2. D. J. Stevenson, T. Spohn, G. Schubert, *Icarus* **54**, 466 (1983).
3. T. M. Donahue, J. H. Hoffman, R. R. Hodges, Jr., A. J. Watson, *Science* **216**, 630 (1982).
4. J. F. Kasting and J. B. Pollack, *Icarus* **53**, 479 (1983); D. M. Hunten, T. M. Donahue, J. C. G. Walker, J. F. Kasting, in *Origin and Evolution of Planetary and Satellite Atmospheres*, S. K. Atreya, J. B. Pollack, M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, 1989), pp. 386–422.
5. D. H. Grinspoon and J. S. Lewis, *Icarus* **74**, 21 (1988).
6. R. G. Prinn and B. Fegley, *Annu. Rev. Earth Planet. Sci.* **13**, 171 (1987).
7. Y. Z. Zhang and A. Zindler, in preparation. This hypothesis is based on results from studies by N. I. Khitarov and A. A. Kadik, *Contrib. Mineral. Petrol.* **41**, 205 (1973); A. Jambon, H. Weber, O. Braun, *Geochim. Cosmochim. Acta* **50**, 401 (1986); E. M. Stolper and J. R. Holloway, *Earth Planet. Sci. Lett.* **87**, 397 (1988).
8. C. C. Counselman, *Astrophys. J.* **180**, 307 (1973).
9. T. M. Donahue and J. B. Pollack, in *Venus*, D. M. Hunten, L. Colin, T. M. Donahue, V. I. Moroz, Eds. (Univ. of Arizona Press, Tucson, 1983), pp. 1003–1036.
10. G. W. Wetherill, *Science* **228**, 877 (1985).
11. W. M. Kaula, in *The Origin of the Earth*, H. Newsom and J. Jones, Eds. (Lunar and Planetary Institute, Houston, in press).
12. D. J. Stevenson, *Annu. Rev. Earth Planet. Sci.* **13**, 271 (1987).
13. A. G. W. Cameron, *Icarus* **56**, 195 (1983).
14. W. Benz, W. L. Slattery, A. G. W. Cameron, *ibid.* **66**, 515 (1986); *ibid.* **71**, 30 (1987); W. Benz, A. G. W. Cameron, H. J. Melosh, *ibid.* **81**, 113 (1989).
15. J. C. G. Walker, *ibid.* **68**, 87 (1986).
16. V. S. Safronov, *Evolution of the Proplanetary Cloud and Formation of the Terrestrial Planets* (NASA Publication TT71-55049, National Aeronautics and Space Administration, Washington, DC, 1972); E. Öpik, *Ir. Astron. J.* **10**, 190 (1972); G. W. Wetherill, *Annu. Rev. Astron. Astrophys.* **18**, 77 (1980); H. Mizuno and A. P. Boss, *Icarus* **63**, 109 (1985); W. M. Kaula and A. E. Beachey, in *Origin of the Moon*, W. K. Hartmann, R. J. Phillips, G. J. Taylor, Eds. (Lunar and Planetary Institute, Houston, 1986), pp. 567–576.
17. Y. A. Surkov, in *Venus*, D. M. Hunten, L. Colin, T. M. Donahue, V. I. Moroz, Eds. (Univ. of Arizona Press, Tucson, 1983), pp. 154–158.
18. D. L. Anderson, *Phys. Today* **42** (no. 3), 38 (1989).
19. D. J. DePaolo, *Geophys. Res. Lett.* **10**, 705 (1983); D. G. Howell and R. W. Murray, *Science* **233**, 446 (1986).
20. D. L. Anderson, *Geophys. Res. Lett.* 7, 102 (1980); *ibid.* **8**, 309 (1981); R. J. Phillips, W. M. Kaula, G. E. McGill, M. C. Malin, *Science* **212**, 879 (1981).
21. W. M. Kaula, *Lunar Planet. Sci.* **19**, 593 (1988).
22. H. Masursky *et al.*, *J. Geophys. Res.* **85**, 8232 (1980).
23. L. S. Crumpler, J. W. Head, D. B. Campbell, *Geology* **14**, 1031 (1986); A. T. Basilevsky and J. W. Head, *Annu. Rev. Earth Planet. Sci.* **16**, 295 (1988); J. W. Head, *Lunar Planet. Sci.* **20**, 396 (1989); E. R. Stofan *et al.*, *Geol. Soc. Am. Bull.* **101**, 143 (1989); D. B. Campbell *et al.*, *Science* **246**, 373 (1989).
24. V. I. Moroz, in *Venus*, D. M. Hunten, L. Colin, T. M. Donahue, V. I. Moroz, Eds. (Univ. of Arizona Press, Tucson, 1983), pp. 45–68.
25. J. W. Head III and L. S. Crumpler, *Science* **238**, 1380 (1987); L. S. Crumpler and J. W. Head, in preparation.
26. W. M. Kaula and R. J. Phillips, *Geophys. Res. Lett.* **8**, 1187 (1981).
27. R. E. Grimm and S. C. Solomon, *J. Geophys. Res.* **94**, 12,103 (1989).
28. W. S. Kiefer and B. H. Hager, *Lunar Planet. Sci.* **20**, 520 (1989).
29. M. T. Zuber, *J. Geophys. Res.* **92**, 541E (1987); W. B. Banerdt and M. P. Golombek, *ibid.* **93**, 4759 (1988); D. R. Williams, *Lunar Planet. Sci.* **19**, 1275 (1988).
30. N. L. Carter and M. C. Tsenn, *Tectonophysics* **136**, 27 (1987).
31. S. H. Kirby and A. K. Kronenberg, *Rev. Geophys.* **25**, 1680 (1987). Dry crustal minerals at 1000 K and a stress of 10^6 Pa range in viscosity from 3×10^{11} to 5×10^{21} Pa-s, compared to 10^{23} Pa-s for olivine.
32. P. Bird, *Science* **239**, 1501 (1988); *J. Geophys. Res.* **94**, 3967 (1989).
33. R. E. Grimm and S. C. Solomon, *J. Geophys. Res.* **93**, 11,911 (1988).
34. S. E. Smrekar and R. J. Phillips, *Eos* 70, 1334 (1989).
35. B. G. Bills, W. S. Kiefer, R. L. Jones, *J. Geophys. Res.* **92**, 10,335 (1987); W. M. Kaula, *Geophys. Res. Lett.* **11**, 35 (1984). The ADCs are derived under the assumption that the compensation of topography is concentrated at one depth (Airy isostasy). The ADCs are averages for compensation that actually is spread out vertically, since it must be mainly "dynamic": the thermal expansions and viscous stresses of the mantle flow system. The ADC c_ℓ for degree ℓ is: $c_\ell = r_\ell S_\ell(V)/S_\ell(H)/A_\ell$, where r_ℓ is the correlation between gravity V and topography H for degree ℓ, S_ℓ is the root-mean-square magnitude, and the factor $A_\ell = 4\pi G\rho(\ell + 1)/gR(2\ell + 1)$, where G is the gravitational constant, ρ is density, g is the acceleration due to gravity, and R is radius (or distance).
36. R. J. Phillips, *Geophys. Res. Lett.* **13**, 1141 (1986); *Lunar Planet. Sci.* **20**, 842 (1989).
37. W. S. Kiefer, M. A. Richards, B. H. Hager, B. G. Bills, *Geophys. Res. Lett.* **13**, 14 (1986).
38. E. M. Stolper, D. Walker, B. H. Hager, J. F. Hays, *J. Geophys. Res.* **86**, 6261 (1981); S. M. Rigden, T. J. Ahrens, E. M. Stolper, *Science* **226**, 1071 (1984); *J. Geophys. Res.* **93**, 367 (1988); *ibid.* **94**, 9508 (1989); D. L. Heinz and R. Jeanloz, *ibid.* **92**, 11,437 (1987); C. B. Agee and D. Walker, *ibid.* **93**, 93 (1988); D. Walker, C. B. Agee, Y. Zhang, *ibid.*, p. 313.
39. D. J. Stevenson and S. C. McNamara, *Geophys. Res. Lett.* **15**, 1455 (1988); D. L. Turcotte, *J. Geophys. Res.* **94**, 2779 (1989).
40. R. E. Grimm and S. C. Solomon, *Geophys. Res. Lett.* **14**, 538 (1987); B. Fegley and R. G. Prinn, *Nature* **337**, 55 (1989).
41. L. W. Esposito, *Science* **223**, 1072 (1984).
42. The component $I_{\ell m}$ of a gravity coefficient $V_{\ell m}$ that is uncorrelated with the topography $H_{\ell m}$ will be: $I_{\ell m} = V_{\ell m} - r_\ell S_\ell(V)H_{\ell m}/S_\ell(H)$, where r_ℓ and S_ℓ are defined in (*35*). The value implying equal stresses will be $(g_E/g_V)^2$ times the value for Earth: one ratio is for the stress, and the other is for the nondimensionalizing of $V_{\ell m}$.
43. D. Bercovici, G. Schubert, G. A. Glatzmaier, *Science* **244**, 950 (1989). The phrase ". . . in the Earth's Mantle" in the title is a misnomer; the constant viscosity makes the paper more applicable to Venus.

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