THE GEOPHYSICS OF VENUS

Impact craters on Venus's surface are surprisingly unscarred by tectonic deformation and volcanic flows. Data from the Magellan mission may help discriminate between catastrophic and evolutionary explanations of the planet's recent placidity.

Sean C. Solomon

Venus is the planet most similar to the Earth in mass, radius and solar distance. Current theories of the early evolution of the solar system suggest that Earth and Venus each formed by the accretion of planetesimals—small rocky or rock–metal objects—that collectively constituted a well-mixed sample of material condensed from the inner solar nebula. The bulk compositions of the two planets should thus be similar. The rates of internal heat generation and the energy available to drive interior convection should also be similar. An important difference between the two planets, however, is the character of their atmospheres. The mass of the dominantly CO_2 atmosphere of Venus is two orders of magnitude greater, as a fraction of planet mass, than that of Earth's atmosphere, and the surface temperature is 450 K higher, a consequence of continuous global cloud cover and a runaway greenhouse effect. The mass of H_2O in a vertical column of unit area is four to five orders of magnitude less for Venus's atmosphere than for the atmosphere and hydrosphere on Earth. As a result, the surface of Venus lacks a water cycle, and the processes of weathering, erosion and sediment transport that dominate terrestrial landforms are comparatively unimportant.

On Earth, the surface manifestation of interior convection is the steady relative motion of the tectonic plates, which separate at midocean ridges, converge at deep-sea trenches and active mountain belts, and slip horizontally past one another along great fault zones. The recycling of oceanic plates at convergence zones and their renewal at midocean ridges serve to resurface the Earth's ocean floor continuously, replacing the entire seafloor in about 10^8 years. The Earth's continents, underlain by thick buoyant crust, do not participate significantly in that recycling and thus preserve rocks as old as 4×10^9 years as well as a long and complex history of deformation, igneous activity, erosion and sedimentation. To what extent do the large-scale deformational, or tectonic, patterns of Venus, with a similar internal heat budget but with very different surface conditions, resemble those of the Earth?

That question was among several that motivated the Magellan mission to Venus. A thick cloud cover precludes optical studies of the Venusian surface from Earth or from orbit, but a series of Earth-based and orbital radar experiments dating back nearly three decades demonstrated that radar imaging could yield important information on the planet's geology. The Magellan mission was designed to image the surface by illuminating it with radar and measuring the reflected brightness, at a horizontal resolution of 100–300 meters, and to map the surface elevation at a vertical resolution of about 80 m and a horizontal resolution of about 10 km. A single radar system accomplished both objectives.[1] For imaging, a high-gain antenna looked sideways in a "synthetic aperture" mode: As the spacecraft moved along its orbit, multiple returns of the transmitted pulsed signal from the same spot on the surface were saved and summed to simulate a larger antenna aperture, thus yielding a better resolution. For mapping the surface elevation, a second low-gain antenna transmitted vertically downward and measured the time it took for the signal to be reflected back.

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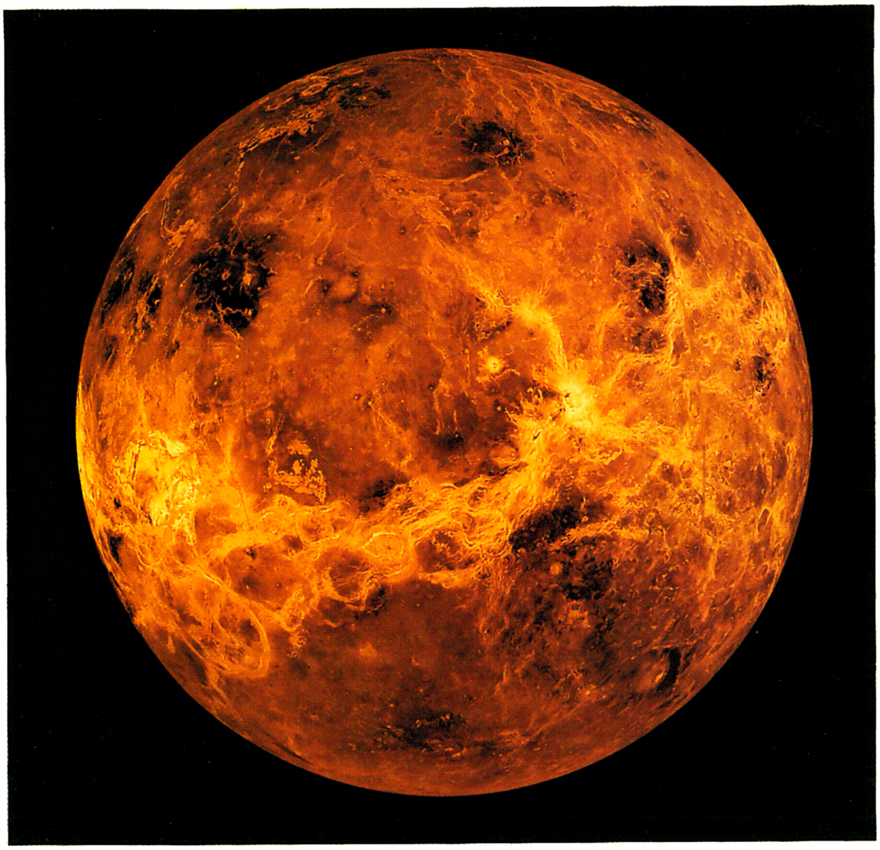


Global view of the surface of Venus. To produce this image, Magellan radar images taken over a two-year period were digitally combined into a mosaic that was then projected onto a simulated globe centered at longitude 180° E. The use of false color enhances small-scale features. The bright features that cross from lower left to upper right are the highlands, coronas and rift valleys of Aphrodite Terra. **Figure 1**

The Magellan spacecraft was placed into a nearly polar orbit about Venus on 10 August 1990 and began mapping about one month later. In each successive "cycle" of 243 Earth days Venus turned once on its axis beneath the plane of the spacecraft orbit. By the end of the first three cycles in September of last year, Magellan had imaged 98% of the Venus surface (see figure 1). At the start of the fourth cycle the elevation of the spacecraft orbit at periapsis—the point of closest approach—was lowered to 180 km, and at regular intervals the high-gain antenna was pointed toward the Earth through periapsis passage to permit the measurement of spacecraft accelerations produced by the gravitational field of Venus.

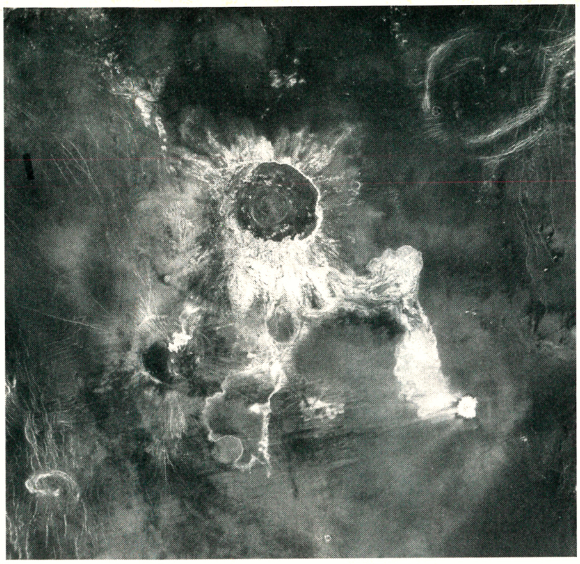
Surface age

Information on the age of the surface provides a critical context for interpreting the geological record of a planet. For Venus, in the absence of returned rock samples whose ages could be determined radiometrically by isotope geochemistry, the only measure of surface age is the density of impact craters.[2,3] As expected on the basis of earlier data and theoretical models, Magellan revealed that impact craters smaller than about 30 km in diameter are deficient relative to larger craters on Venus, because of the severe decrease in the kinetic energy of small meteoroids during transit through the dense Venusian atmosphere. The areal density of craters larger than 30 km in diameter, together with estimates of cratering rate scaled from the Earth and Moon or taken from the known population of Venus-crossing asteroids,[4] indicates an average surface age of about 5×10^8 years, or 10% of the age of the solar system. This age, greater than that of the Earth's ocean floor but less than the radiometric age of the Earth's continental rocks or the surface age of the smaller terrestrial planets, is in itself not remarkable for a planet with a hot, dynamic interior, like the Earth, albeit one on which erosion is unimportant.

More remarkable is that the spatial distribution of craters of all sizes is indistinguishable from a random population, and that most of them have not been significantly modified by tectonic deformation or by volcanic flows external to the crater rim,[2,3] despite evidence from Magellan images that volcanic[5] and tectonic[6] features are widespread on Venus. (An example of such an impact crater is Isabella, shown in Figure 2.) One interpretation of these characteristics, championed by Gerald Schaber and colleagues,[3] is that most of the surface dates from the end of a global resurfacing event that ceased about 5×10^8 years ago, and that volcanic and tectonic activity since then has been at much lower levels. A contrasting view, advanced by Roger Phillips and coworkers,[2] is that the Venusian surface exhibits a spectrum of ages. (Figure 3 compares the surface age distributions expected under these two scenarios.) This view is supported by the observations that modified craters tend to be located in areas of low crater density and that low crater density appears to be correlated with increased radar backscatter—an indication of high topography and high roughness, both thought to be signatures of comparative geological youth. The paucity of small craters, however, prevents one from using crater density to determine with confidence the relative ages of geological units, as has been done for the solid planets and satellites lacking a significant atmosphere.

Tectonics

Magellan has revealed that tectonic features of a wide variety of styles and spatial scales are present over most



Impact crater Isabella in a Magellan radar image. Isabella (centered near 30° S, 204° E) is the second largest crater on Venus at approximately 175 km in diameter. Radar-bright, rough-textured ejecta extending up to two crater radii from the crater center and the remarkable bright flow features extending hundreds of kilometers from the crater walls are thought to date from the impact event[3] and have not been subsequently modified to any significant degree by deformation or volcanism exterior to the crater. The generally radar-dark, smooth floor of the crater may contain younger volcanic deposits that were deformed after emplacement to produce the concentric pattern of faults. This and all subsequent radar images are in sinusoidal equal-area projection; north is up, and the radar illumination direction is from the left. The incidence angle of the radar is about 33° for this image and in general is a function of latitude.[1] **Figure 2**

of the Venusian surface.[6] Deformation is manifested in areally distributed strain of modest magnitude, accommodated by families of faults and folds, spaced at a few to a few tens of kilometers and often coherent over hundreds of kilometers, in many volcanic plains. Deformation is also commonly evident as zones of more intense horizontal shortening or extension of the crust. Ridge belts and mountain belts, marked by many closely spaced folds and thrust faults, represent successive degrees of local shortening and crustal thickening. Ridge belts have characteristic widths and spacings of hundreds of kilometers and up to 1 km of relief. Mountain belts are comparable in relief and horizontal dimensions to those on Earth, and likewise they often show evidence of having undergone lateral extension both during and after active crustal compression (because elevated terrain tends to spread in response to gravitational stress).

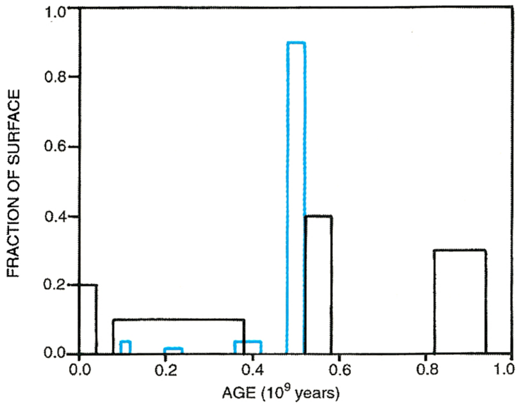
Venus displays two principal geometric variations on large-scale extension: quasicircular corona structures 75–2600 km in diameter and broad rises with linear rift zones hundreds to thousands of kilometers in length. The rift zones (see figure 4) have dimensions and relief similar to intracontinental rift zones on Earth, such as the East African or Rio Grande rifts, but the coronas (see figure 5) have no evident terrestrial counterpart. Both are sites of significant volcanic flux, but horizontal displacements in the rift zones (inferred from rift valley geometry and offsets of older features) may be limited to only a few tens of kilometers. Few large-offset strike–slip faults like the San Andreas Fault are observed on Venus, but limited local horizontal shear has been accommodated across many zones of crustal stretching or shortening. Many elevated areas are characterized by extremely complex, intersecting patterns of tectonic features at a range of scales (see figure 6); these regions record multiple stages of strain of diverse geometries. Several large-scale tectonic features have topographic slopes in excess of 20°–30° over a 10-km horizontal scale. Numerical models simulating the relaxation of such steep slopes by ductile flow in the middle to lower crust[7] suggest that such regions were tectonically active within the last 10^7 years.

In general the preserved record of global tectonics of Venus does not resemble oceanic plate tectonics on Earth, wherein large rigid plates are separated by narrow zones of active deformation generally no more than a few kilometers across. Rather, tectonic strain on Venus typically involves deformation distributed across broad zones tens to hundreds of kilometers wide, separated by comparatively undeformed blocks having dimensions of hundreds of kilometers. These characteristics are shared with actively deforming continental regions on Earth. This similarity in tectonic styles does not imply that the crust on Venus is similar in composition to that of the Earth's continents—only that both crusts display a broadly similar response to tectonic stress. In fact, chemical analyses of surface samples to accuracies of a few percent, made on site during several Soviet lander missions using x-ray fluorescence and gamma-ray spectroscopy, indicate compositions generally nearer to that of Earth's oceanic crust than to terrestrial continental material.[8] On Earth, the continental plates are weaker than oceanic plates because of the greater thickness of crustal material, which at a given temperature deforms at significantly higher rates than does the underlying mantle. On Venus, the high surface temperature is expected to lead to ductile behavior at significantly shallower levels in the middle to lower crust than on Earth and is probably responsible for the rich spectrum of deformational features.

Gravity anomalies

The deviation of a planet's gravity field from that expected for a rotating fluid body of radially varying density is known as the gravity anomaly. Its correlation with the topography provides clues to the internal density structure of the planet. The mass of the topography exerts a pressure on the underlying rock. In the theory of isostasy, there is a depth at which pressure is assumed to be uniform, because over geological time scales the rock behaves as a fluid. Thus the excess pressure exerted, for example, by a highland area must be "compensated" by a zone of lower-than-average density underneath. Because crustal material is less dense than underlying mantle material, a common form of such compensation is a crust extending deeper into the mantle. Regions with higher temperatures are also of lower density and can help to compensate. Isostasy is basically a static theory; in addition, there may be contributions to gravity anomalies from convective stresses. An upwelling region will have positive contributions to gravity from

Surface age distributions on Venus under two scenarios. In the catastrophic resurfacing scenario (blue histogram), most of the surface is about 5×10^8 years old, but small areas are younger. In an alternative, more gradual resurfacing scenario[2] (black histogram), there is a more widespread distribution of surface ages, from 0 to approximately 10^9 years. Both scenarios are broadly consistent with the distribution and states of preservation of impact craters on Venus. (Courtesy of Roger Phillips, Washington University, St. Louis.) **Figure 3**



the elevated surface and a negative contribution from the lower density in the hot rising column of mantle. The net gravity anomaly from dynamic processes in the mantle is a function of the radial (and lateral) variation in the viscosity of mantle material.

Measurements of the anomalies in the gravitational field made by the Pioneer Venus orbiter, and now confirmed by the first eight months' worth of Magellan data, indicate that the interior dynamics of Venus differs from that of the Earth in important respects. In contrast to the situation on Earth, topography and gravity on Venus are strongly correlated on scales (or "wavelengths") of several hundred to several thousand kilometers.[9] Further, many major features have a large ratio of gravity anomaly to topographic relief,[10] indicating that topographic variations are compensated by interior density variations at depths of up to several hundred kilometers. Density variations associated with convective upwelling and downwelling deep in the upper mantle must be involved. On Earth, the compensation depths are much smaller—tens of kilometers—and imply that beneath the lithosphere (the mechanically strong outer layer that generally includes the crust and some thickness of uppermost mantle) is a layer of low viscosity that does not transmit stresses from the bulk of the mantle underneath. (This low-strength zone probably accounts for the horizontal mobility of the Earth's plates.) Researchers have interpreted the large compensation depths on Venus to mean that Venus lacks such an upper-mantle low-viscosity zone,[11] so that convective motions deep in the upper mantle are able to couple into the overlying lithosphere[12] and cause long-wavelength vertical distortions of the surface. The absence of a low-viscosity zone restricts horizontal mobility and probably accounts for the large-scale coherence of surface strains on Venus.[6]

The large ratios of long-wavelength gravity anomaly to long-wavelength topographic relief have been taken as evidence that the crust and upper mantle of Venus may generally be stronger than one would infer from simple thermal models that extrapolate Earth's interior heat flow to Venus's 450-K-greater surface temperature.[13] There is other evidence in support of this view. The measured depths of impact craters are generally too great to be consistent with significant relaxation of relief by flow of crustal material,[14] such as might be expected if temperatures in the lower crust were sufficiently great

Northern Beta Regio, a rifted highland region, in a Magellan radar image. The image is centered at about 33° N, 283° E, and is 750 km wide. The radar-bright areas consist of a fabric of closely spaced families of faults and folds of various trends. This terrain has been extended in the east–west direction, leading to the formation of north–south-trending faults and of the steep-sided rift valley (with east-facing walls nearly in radar shadow) visible in the center of the image. The rift-related faults splay to the northwest and northeast in the northern part of the region shown. Dark patches are smooth and are inferred to be volcanic deposits overlying the older, bright terrain. **Figure 4**

The Idem–Kuva corona structure in a Magellan radar image. The corona, centered at 25° N, 358° E, is about 230 km in diameter. Corona structures are distinguished by an annulus of deformed terrain and frequently by an elevated interior.[6] Radar-bright volcanic flows emanate from topographic highs of more than 1 km relief in the eastern and western portions of this structure. **Figure 5**

to permit high rates of ductile strain. Estimates of the flexural rigidity of the lithosphere—made from the shapes of topographic profiles across the curved troughs marking the margins of several corona structures—are comparable to the rigidity of oceanic lithosphere at deep-sea trenches on Earth.[15] This result is surprising, because researchers think the base of the mechanically strong lithosphere is defined by the temperature marking the onset of significant ductile flow over geological time scales. This temperature, about 1000 K on Earth, would normally be expected to occur at shallower levels on Venus, because of its hotter surface. One possible explanation is that the topographic profiles are being interpreted incorrectly: Ductile flow accompanying gravitational relaxation of relief, for instance, can deform the surface in a manner that mimics elastic plate flexure.[7] If real, a stronger-than-expected lithosphere on Venus could result from a lesser rate of heat loss (per planet mass) than on Earth, or it could indicate that under extremely anhydrous conditions crustal and mantle rocks are significantly more resistant to flow than they are in the Earth's crust and mantle.

Catastrophic resurfacing hypotheses

Hypotheses advanced to explain the tectonics of Venus, and in particular the resurfacing history, fall into two categories: catastrophic and evolutionary. Those in the former category explain the small fraction of impact craters modified by exterior volcanism or significant deformation as the result of a global-scale resurfacing event that ended about 5×10^8 years ago.[3] In one class of such scenarios, catastrophic resurfacing occurs because of an instability in the lithosphere. Donald Turcotte[13] has proposed that global lithospheric overturn—a version of plate tectonics in which the entire lithosphere sinks into the underlying mantle and is replaced by hot new material—operates episodically on Venus and that for the last 5×10^8 years the lithosphere has been cooling and mechanically stable. He argues that a cool and thick lithosphere is in better agreement with the large values of the flexural rigidity of the lithosphere and the large ratios of long-wavelength gravity anomaly to long-wavelength topographic relief than is a lithosphere in steady-state conductive equilibrium with the long-term average heat flow from the interior.

Marc Parmentier and Paul Hess[16] have suggested that melt extraction can decrease the density of the lithospheric mantle and thus initially stabilize the floating lithosphere; subsequent cooling may increase the mantle density enough to make the lithosphere unstable. Global overturn of this unstable layer would be followed by widespread partial melting of the upper mantle, global volcanic resurfacing and the gradual development of a new buoyant layer of lithospheric mantle that gives rise to another extended period of lithospheric stability. In one-dimensional models of this process,[16] the time between lithospheric instability events is $3–5 \times 10^8$ years. One problem with these one-dimensional models is that they assume global synchroneity. Even if such instability mechanisms are operative, it is likely that different parts of the planet will be at different stages in the stabilization and destabilization sequence and that such regional differences will smooth out global-scale temporal variations.

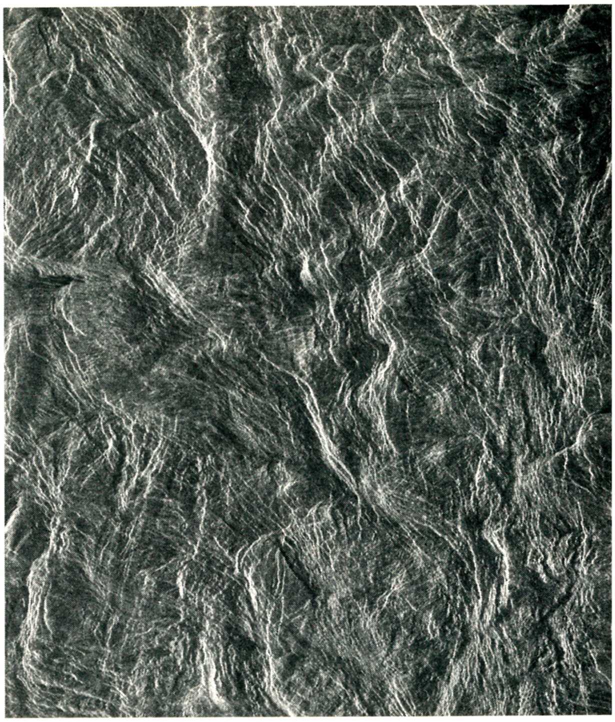
In other catastrophic scenarios, time-variable mantle convection rather than lithospheric instability serves as the mechanism for global resurfacing. An early effort by Jafar Arkani-Hamed and Nafi Toksöz[17] to simulate time-variable, three-dimensional mantle convection on Venus led to models in which the characteristic flow speed and mantle heat flux showed large oscillations (by factors of 2–10) at intervals of $1–2 \times 10^8$ years. In improved calculations with better spatial resolution, mantle convection, while still time varying, shows significantly lesser fluctuations, by one order of magnitude.[18]

Volker Steinbach and David Yuen[19] have drawn attention to the role that pressure-induced changes in upper-mantle mineralogy may play in governing the radial character of mantle convection in the large terrestrial planets. They argue that such phase changes cause separate convecting layers to form in the upper and lower mantle, but that as the Rayleigh number of the mantle (which measures the strength of thermal buoyancy in driving flow relative to the tendencies for viscosity to resist flow and for heat conduction to reduce buoyancy) decreases in response to the cooling of the central metallic core, whole-mantle convection tends to become favored over layered convection. If Venus cooled more rapidly than Earth early in its history, it may now have a lesser mantle Rayleigh number and have gone through a transition to whole-mantle convection, while the Earth may still be characterized by layered mantle flow. Such a transition would have been accompanied by overturn of the upper mantle, the upward transport of significant heat, the generation of substantial melt and probably global volcanic resurfacing.[19]

Evolutionary hypotheses

The second category of resurfacing scenarios involves only a gradual lessening of volcanic or tectonic activity rather than one or more global catastrophes. There are several motivations for such evolutionary scenarios. While the known volcanic histories of Earth[20] and Mars[21] include periods of greater-than-average activity and presumably therefore time-variable mantle convective flux, no other

Heavily deformed terrain in an upland area known as Tellus Regio. This Magellan radar image, 80 km wide, is centered on 39.5° N, 85.7° E. The terrain is dominated by extensional fault structures trending north to northwest. Several northeast-trending topographic ridges may be remnants of earlier products of horizontal shortening. This type of complexly deformed terrain is typical of many highland regions on Venus. **Figure 6**



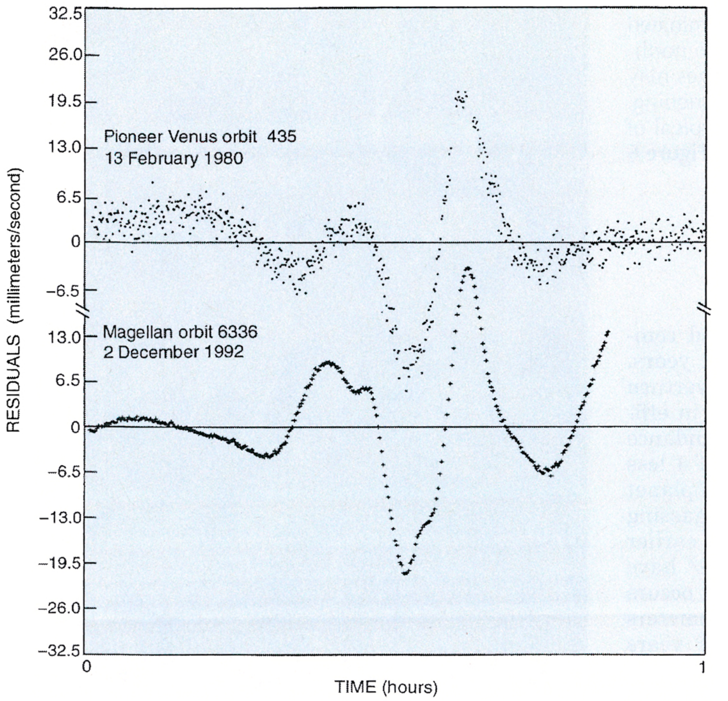
terrestrial planet displays evidence for rapid and complete global resurfacing during the past 4×10^9 years. Furthermore, global resurfacing by large-scale overturn of the lithosphere or upper mantle should result in efficient outgassing of the upper mantle; the ^{40}Ar abundance of the Venusian atmosphere—which is a factor of 4 less than that of the Earth's atmosphere as a fraction of planet mass—suggests that any such widespread outgassing should have been restricted to times significantly earlier than 5×10^8 years ago.[22] Phillips and coworkers[2] have described a model in which volcanic resurfacing occurs episodically in small patches a few hundred kilometers in extent, with a characteristic time of order 10^5 years between events. They argue that such a model, involving a gradual decline in the volcanic flux of the planet, is as consistent with the characteristics of impact craters on Venus as are the catastrophic scenarios.

I have recently advanced the hypothesis that, at least in the geologically recent past, the primary resurfacing mechanism on Venus has been tectonic deformation rather than volcanism.[23] An important difference between Venus and all of the other terrestrial planets is its high surface temperature. Characteristic time scales for ductile deformation of crustal and mantle material are known to vary exponentially with reciprocal temperature; so, for a given thermal gradient and stress field, high rates of ductile flow are expected at much shallower levels on Venus than on other terrestrial planets. Direct coupling of mantle convective stresses[12] should give rise to lithospheric strains that are broadly coherent over large regions. For a sufficiently weak lower crust, such stresses should also cause high rates of lower-crustal deformation and thus high rates of surface strain.

Therefore if the surface temperature prior to the era of Venus history now preserved was comparable to that at present, the higher heat flow—associated with early planetary cooling, enhanced radiogenic heat production and a mantle convective vigor at least that of the present—should have led to geologically rapid rates of crustal deformation over most, and perhaps all, of the surface. Such an era would have been characterized by a nearly global extent of intensely deformed terrain (such as that in figure 6) and few impact craters undeformed enough to be recognizable from surface images. At some point in the evolution of Venus under this scenario, however, heat flow declined to levels sufficiently low that the ductile strength of the lower crust increased significantly, so that rates of deformation that had been high on geological time scales became much lower. Following such a transition, which may have been abrupt in the geological record because of the exponential dependence of strain rate on temperature, both volcanic deposits and impact craters would have persisted for long intervals with at most modest deformation. The characteristics of the Venus surface as revealed by Magellan are consistent with this hypothesis if such a transition occurred about 5×10^8 years ago.

This tectonic resurfacing hypothesis implies a rapid change on a nearly planetary scale from high rates of resurfacing to low rates, as is called for by the catastrophic resurfacing model,[3] but it involves no true catastrophe—and certainly no global outpouring of magma. If Venus were laterally uniform in both crustal thickness and heat flow, then the transition would be expected to have occurred with global synchroneity. While the surface today is not strictly uniform, more than 80% of it stands at elevations within 1 km of the mean value. To the extent that regions at similar elevations have similar crustal thicknesses and thermal structures and that the principle of isostasy applies, the surface of Venus may not depart greatly from uniformity, and an apparently catastrophic, nearly global transition is not a bad first approximation.

Departures from global synchroneity are also to be expected. In particular, highland regions, whether they owe their elevations primarily to greater crustal thickness or to enhanced temperatures at depth, should persist as regions of high strain rate long after the rate of deformation in lowland plains regions has dropped to modest levels. Lowlands should thus be preferred sites for the preservation of relatively undeformed volcanic deposits and impact craters, as is observed.[2] In light of the tectonic resurfacing hypothesis the unusual cratering record on Venus is thus seen to be a consequence primarily of the atmospheric greenhouse and its effect on the surface temperature and the rheology of the crust. No catastrophic internal event or recent episode of extensive interior outgassing is called for. By this hypothesis the resurfacing history should nonetheless contain elements of both the "catastrophic" and "gradual" scenarios for crater removal, with approximately synchronous stabilization of lithosphere beneath plains regions of average elevation and more recent tectonic activity in highlands.



Tracking data from the Pioneer Venus orbiter and Magellan used to determine the gravity field of Venus. Each plot displays measurements of the line-of-sight velocity of the spacecraft, obtained from Doppler shifts in the transmitter carrier frequency, after removing the velocity signal of the best-fitting orbital arc. The two plots compare orbits at nearly the same longitude (87° E) and spacecraft periapsis altitude (175 km). The superior signal-to-noise ratio of the Magellan data is due to the significantly reduced influence of plasma effects in the Venus ionosphere at Magellan's higher carrier frequency (8.4 GHz versus Pioneer's 2.2 GHz). (Courtesy of William L. Sjogren, Jet Propulsion Laboratory.) **Figure 7**

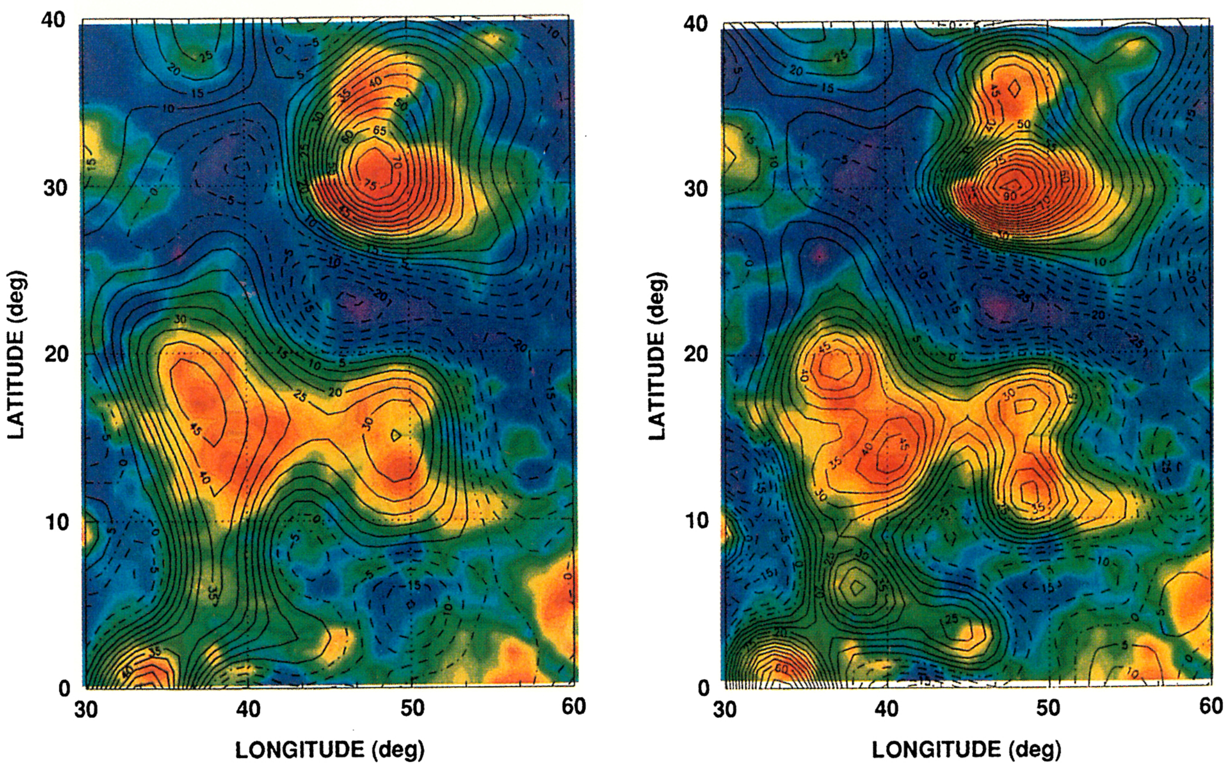
High-resolution gravity measurements

Measurements Magellan is now making of the gravity field of Venus may help us to choose among these hypotheses. The earlier Pioneer Venus mission determined the long-wavelength components of the gravity field, and Magellan has now confirmed them. Variations in the gravity field at shorter wavelengths are sensitive to the thickness and structure of the upper boundary layer of mantle convection, which in turn are related to both the average and local heat flux from the mantle. From the relationship between gravity anomaly and topographic relief—both on a regional basis and across large features such as coronas, rift zones and mountain belts—it is possible in principle to distinguish between interior thermal models that differ in the thickness and strength of the mechanically strong lithospheric layer. Key wavelengths for this discrimination are several hundred kilometers and less; one can determine such variations in the gravity field by tracking an orbiting spacecraft at elevations comparable to or less than the wavelengths involved.

The Magellan spacecraft is yielding gravity data that are significantly better than those obtained by Pioneer Venus, for two reasons. First, while both the Pioneer Venus and Magellan spacecraft were placed in eccentric orbits with near-equatorial latitudes at periapsis, the eccentricity of the Magellan orbit is far less, so the spacecraft elevation at high latitudes is much lower. Second, the transponder Magellan uses to determine gravitational accelerations operates with an X-band carrier frequency (8.4 GHz), which is much less susceptible to plasma-induced noise in the Venus ionosphere than is the S-band carrier frequency (2.2 GHz) used by Pioneer Venus. As a result the signal-to-noise ratio is much higher for the Magellan data (see figure 7). Early Magellan data are already yielding gravity field solutions that show improved resolution and interpretability of anomalies over those available from Pioneer Venus data alone (see figure 8).

Because of the elliptical orbit of the Magellan spacecraft, the gravity data collected during the cycle that ended in late May of this year have good spatial resolution only near the periapsis latitude (10° N). Resolution degrades progressively with increasing latitude to the north and south and is no better than 10^3 km at high latitudes, including such areas as the Ishtar Terra highland, which contains the only examples of large mountain belts on Venus. A global set of gravity measurements of uniformly good resolution, and thus a global view of the thermal and mechanical properties of the interior, requires tracking data from a spacecraft in low circular orbit.

While the Magellan spacecraft does not have sufficient propellant to make its orbit circular by purely propulsive means, Magellan project engineers have developed a novel and ambitious scheme to circularize the orbit by means of aerodynamic drag. This scheme, currently being carried out, involves lowering the periapsis elevation into the upper Venusian atmosphere; relying on drag to reduce periapsis speed and lower apoapsis elevation (the farthest point in the orbit), while maintaining periapsis elevation by means of small propulsive maneuvers; and finally propulsively raising periapsis out of the atmosphere once the apoapsis elevation has been lowered sufficiently. This aerobraking scheme should leave Magellan in an approximately circular orbit of about 200–300 km elevation by the end of this month. Tracking the spacecraft for 360° of longitude in such a circular orbit will yield a gravity field of uniformly good coverage and resolution by the end of this month. While NASA's continued support of data acquisition after orbit circularization has from time to time been in doubt, there is reason to hope that the measurement of a high-resolution global gravity field following a successful aerobraking maneuver will prove to be both scientifically and programmatically compelling to the agency.



a b

Two gravity field solutions showing the improvement in resolution obtained with recent Magellan data. **a:** Contours of the free-air gravity anomaly, in units of 10^{-5} m/sec^2, for the Bell Regio (north of 25° N) and eastern Eistla Regio (5°–25° N) areas from a solution to the global gravity field obtained from Pioneer Venus orbiter tracking data expanded in spherical harmonics to degree and order 50. The contours are superposed on a color-contoured map of elevations obtained from Magellan altimetry data. **b:** Contours obtained from a new harmonic solution, to degree and order 60, obtained from a combination of Magellan and Pioneer Venus tracking data. Note that the magnitudes of the peak anomalies are greater in **b** and that the gravity anomaly contours show better agreement with the elevation contours. (Courtesy of Sjogren.) **Figure 8**

What is clear from the results of the Magellan mission obtained to date is that the inner workings of Venus manifest themselves at the surface in a fashion very different from that on Earth. While Venus currently lacks global plate tectonics, it has been subjected to a unique resurfacing history that challenges our ability to interpret and explain. Further study of Magellan images, the acquisition of high-resolution gravity field data through a full mission cycle following orbit circularization, and continued development of interior dynamical models should sharpen the competing hypotheses and may lead to an improved general understanding of mantle convection and melting on all of the terrestrial planets, including Earth.

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