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Tectonics and Evolution of Venus

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Summary. The global tectonics of Venus differs significantly from that of Earth, most markedly in that the surface is covered predominately by gently rolling terrain; there apparently are no features like ocean rises; the gravity is positively correlated with topography at all wavelengths; and the few highlands are estimated to be supported or compensated at a depth of approximately 100 kilometers. The surface of Venus appears to be covered mainly by an ancient crust, the high surface temperature making subduction difficult. It seems likely that well over 1 billion years ago water was destabilized at the surface and, soon after, plate tectonics ceased. The highlands appear to be actively supported, presumably as manifestations of long-enduring hot spots.

Radar altimetry and imaging from the Pioneer Venus Orbiter have produced the first comprehensive topographic map of Venus. As of April 1980, this map covered 90 percent of the surface with a horizontal resolution of about 200 kilometers and a vertical accuracy of ±200 meters (*1*). The lateral variations in the gravity field of Venus have also been measured (*2*). Other recent measurements pertinent to the interior of Venus and its evolution include Pioneer Venus Orbiter magnetometry (*3*), Pioneer Venus Probe mass spectrometry (*4*) and gas chromatography (*5*), and more detailed Earth-based radar imaging (*6*).

In this article we synthesize these recent data and earlier data (*7*) to infer the internal state and long-term evolution of Venus. Our interpretation draws heavily on comparison with Earth, but legitimately so, as Venus differs less than 30 percent from Earth in all important bulk properties. It is fascinating that, despite these gross similarities, Venus appears to have evolved so differently from Earth. If there is one outstanding conclusion to be drawn from the recent measurements, it is that Venus is even more different from Earth than previously imagined.

Global Properties of Venus

Tables 1 and 2 give the bulk properties of Venus, Earth, Mars, the sun, and chondritic meteorites relevant to planetary internal structure and evolution. Of these properties, only those pertaining to the abundance of the radioactive element potassium and its daughter product argon entail debatable extrapolations, as discussed below. The properties in which Venus is most strikingly different from Earth are its slow rotation rate, the absence of a satellite, the virtual absence of a magnetic field, the dearth of water in the atmosphere, the abundance of primordial argon ($^{36+38}$Ar), and the high surface temperature.

Figure 1 is a map of the venerean topography, superimposed with contours of the gravity field (*2*). Figure 2 shows the hypsometric curves for Venus and Earth: smoothed histograms of the frequencies of occurrence of topographic elevations. Table 3 gives spectral (spherical harmonic degree l) information about the topography and free-air gravity fields of Venus and Earth, specifically the root-mean-square normalized coefficient σ_l and the degree correlation coefficient r_l (*8*). The topography has one predominant elevation, resulting in a single mode in the hypsometric curve in Fig. 2. We refer to this mode as the Median Plains. The Venus gravity field as mapped to data shows a significant positive correlation with topography. The visual relation, as seen in Fig. 1, is striking for both positive and negative features. Results for the Beta and Ishtar regions show the same strong correlation. This relation is quite unlike that on Earth, where only 10 percent of the long-wavelength gravity is correlated with topography, most of the signal being associated with dynamic mantle processes (*9*).

The proportionate abundance of ^{40}Ar in the atmosphere of Venus is about 30 percent of Earth's (*4*). This lower abundance arises from either a lower initial amount of ^{40}K or a lower proportionate release of the ^{40}Ar generated by decay (*10*). Alternative extreme models are: (i) a Venus with a similar potassium abundance, as tectonically active as Earth, but with lower erosion rates; (ii) a Venus with a similar potassium abundance but less active tectonically; and (iii) a Venus with a lower potassium abundance.

Thermal Regime

Models for support of topographic and gravitational variations on Venus depend on the internal temperature gradient because of the strong temperature dependence of the viscosity. This temperature gradient is, in turn, a consequence of the thermal history of the planet, including the upward differentiation of radioactive heat sources. However, the near-surface temperature curve for Venus, at present and in the Archean era (more than 3 billion years ago), can be calculated from a relatively restricted set of assumptions, using the same methods applied to terrestrial continents (*11, 12*). The slopes of these temperature curves decrease with depth because of the concentration of radioactivity in the crust.

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Table 1. Planetary properties.

Planet	Solar distance* (AU)	Mass† (m_E)	Reduced density‡ (g/cm^3)	Mean radius (km)	Magnetic moment§ (*M*)	Rotation period (days)	Satellites	Surface temperature (K)
Venus	0.72	0.816	3.9	6051	5×10^{-5}	243	0	740
Earth	1.00	1.000	4.03	6371	1.00	1.00	1	280
Mars	1.52	0.108	3.7	3390	10^{-4}	1.03	2	210
Reference			(*46*)	(*1*)	(*3*)			

*AU, astronomical unit (1 AU = 1.5×10^8 km). †m_E, ratio to Earth mass (6×10^{24} kg). ‡Density of the planetary material if it were all at a pressure of 10 kilobars (1.0 gigapascal). §*M*, Earth magnetic moment (8×10^{25} gauss-cm^3; 8×10^{15} tesla-m^3).

A Venus most nearly "equivalent" to Earth in specific (per unit mass) radioactive heat sources would have a lower radioactive heat flux because of its lower total mass of heat sources (*13*), and might have a lower primordial heat flux because it is a smaller planet. The abundance of ^{40}Ar in Table 2 suggests that specific potassium in Venus might be depleted to one-third of that in Earth, but the K/U ratio suggests that it is not depleted at all. However, the total heat flux of the surface of Venus would be relatively insensitive to this particular variation in the abundance of potassium.

Estimates of the residual terrestrial primordial heat can be made from the drop of ~ 200°C in upper mantle temperature in the last 2.5 billion years, estimated from phase relations of rocks (*14*). Taking this temperature change of 200°C with a decay time for primordial heat of 2 billion years, and assuming a Venus-Earth primordial heat ratio of 0.9, gives a present venerean value of 15 ergs per square centimeter per second.

The resulting temperature curves, starting from surface values of 280 K for Earth and 740 K for Venus and calculated numerically because of the pressure and temperature dependence of conductivity, are plotted in Fig. 3.

Since we are interested in evolution as well as present state, we also show in Fig. 3 estimated Archean temperature curves, which are most strongly constrained for Venus by the solidus of ultramafic rocks and for Earth by the observed temperature change of ~ 200°C. The principal unknown for these Archean curves is the surface temperature of Venus. The greenhouse effect depends nonlinearly on the solar temperature, which was lower in the past. A solar temperature sufficient to lead to the high surface temperature could have arisen relatively late in the history of Venus (*15*).

If temperatures sufficient to destabilize water on the surface were attained well over 1.0 billion years ago, the evolution of Venus might have differed long enough for appreciably greater retention of lithophiles near the surface and loss of primordial heat. We therefore show a Venus temperature curve ("early volatile loss") for which primordial and mantle radioactive heat are half as great as in the "equivalent" Venus and crustal heat is greater. As it is also plausible that in a dry Venus the decay depth of crustal radioactivity is greater, we have doubled its value. If venerean temperature gradients vary as much as those suggested for terrestrial continents (*11*, *12*), departures in temperature of ~500°C from the mean are plausible at a depth of 100 km.

A mild constraint on the temperature curve at great depth is the absence of a magnetic field, which indicates core temperatures not significantly lower than those of Earth (*16*).

Compensation Models

The high degree of correlation between gravity and topography on Venus indicates that finite strength, as well as compensation, should be considered in models of internal density distributions that support the topographic loads. In addition, the compensation may be either passive or dynamic. Passive compensation is the classical concept of Airy or Pratt isostasy (*17*), with roots or lower density composition supporting elevated regions. The entire system of topography and compensating zone is stabilized against deformation by being cool enough to resist lateral creep. Alternatively, the topography is dynamically supported by thermal convection, which entails viscous forces and thermal anomalies. On Earth, this process has been inferred from gravity anomalies which indicate that the compensation of certain topographic features extends to depths beneath the seismically determined lithosphere (*18*). However, it is important to note that gravity data alone cannot entirely distinguish between isostatic, dynamic, or finite-strength support of topographic irregularities.

Although isostasy provides a near-minimum in the maximum lithospheric stress, reduction of the maximum shear stress near extreme topography may require substantial compression in the lithosphere so that, in conjunction with the vertical load stress, the resulting stress difference is small. This mechanism has been proposed for support of the Tibetan Plateau (*19*) and may apply to the great topographic heights of Aphrodite and Ishtar on Venus (Fig. 1).

A useful constraint on any internal density model is the admittance function, Z_l, the spectral ratio of gravity (measured at the surface) to topography (*20*). We estimated the admittance (*21*) for three topographic features in the equatorial regions of Venus: western Aphrodite and two isolated smaller features to the northwest. The nondimen-

Table 2. Compositions.

Body	Atomic ratios			Volatile abundance					
	K/U	$^{38}Ar/^{36}Ar$	$^{20}Ne/^{36}Ar$	$^{36+38}Ar$ (g/g)*	^{40}Ar (g/g)	Xe (g/g)	N_2 (g/g)	CO_2 (g/g)	H_2O (g/g)
Venus†	10^4	0.18	0.3	4×10^{-9}	3×10^{-9}		4×10^{-6}	1×10^{-4}	1×10^{-7}
Earth	10^4	0.19	0.6	5×10^{-11}	1×10^{-8}	1×10^{-11}	3×10^{-6}	2×10^{-4}	3×10^{-4}
Mars†	2×10^3	0.2	0.5	2×10^{-13}	5×10^{-10}	1×10^{-14}	1×10^{-7}	$>3 \times 10^{-8}$	$>5 \times 10^{-6}$
Sun			31	1×10^{-4}		2×10^{-8}	1×10^{-3}	1×10^{-2}	1×10^{-2}
Carbonaceous chondrites	4×10^4	0.2	0.1–15	8×10^{-10}		5×10^{-11}			
References	(*13, 28, 29*)	(*4, 47, 48*)	(*4, 47, 48*)	(*4, 47, 48*)	(*4, 47*)	(*47, 48*)	(*4, 5, 47*)	(*47*)	(*5, 47*)

*Grams per gram of body. †Assuming total outgassing.

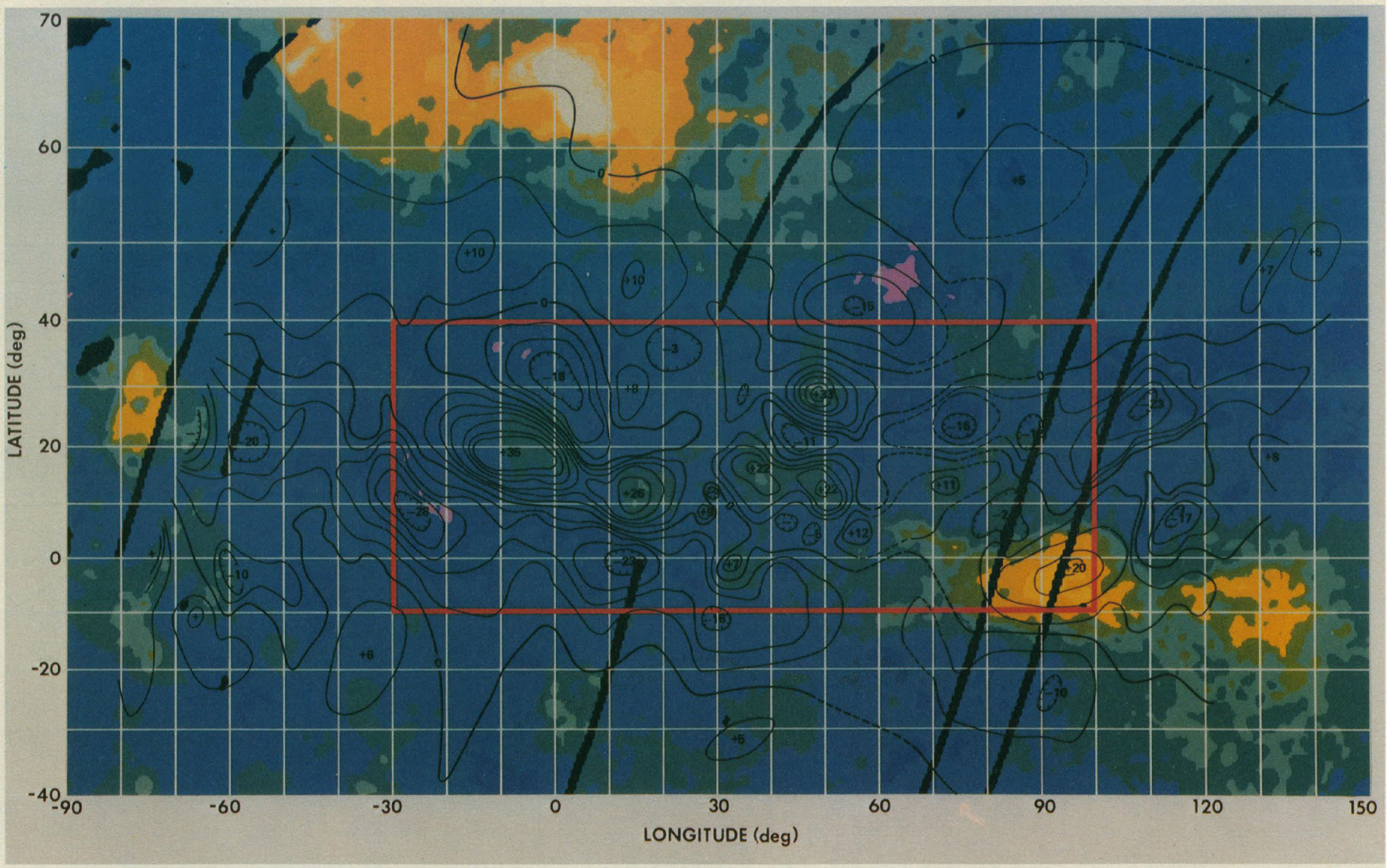


Fig. 1. Contours of the line-of-sight gravity field mapped by Pioneer Venus spacecraft superimposed on a layer tint map of topography [from (5)]. The contour interval is 5 mgal. Loss of resolution at high latitudes is due to high spacecraft altitude. The line-of-sight direction is dominantly vertical to the surface within the red rectangle, so gravity can be directly correlated to the surface beneath it in this region. Topography is in 1-km layers ranging from lavender-pink (low) to white (high). Three major topographic features discussed in this article are Ishtar (top), Aphrodite (lower right), and Beta Regio (center left).

sional admittance estimates and the corresponding wavelengths ($\lambda_l = 2\pi R_0/l$; where R_0 is planetary radius) for the three topographic features are $Z_l = 0.28$ for $\lambda_l = 2700$ km; $Z_l = 0.15$ for $\lambda_l = 4200$ km; and $Z_l = 0.08$ for $\lambda_l = 6000$ km.

The hypothesis most easily tested for the support of Venus topography is a combination of local compensation and regional elastic flexure. Consider a thin elastic spherical shell of thickness t_L, depth to compensating zone t_C, and flexural rigidity D (22). Figure 4 shows curves of D versus t_C for each of the three regions analyzed. The two curves for each region bound an arbitrary choice of t_L values between 50 km (lower curve) and 400 km (upper curve), with the corresponding range of rigidities from 10^{11} to 10^{12} dyne-cm^{-2}, respectively. All three regions show depths of complete compensation of $t_C \sim 115 \pm 30$ km, the variation being close to the formal errors of the estimates. Although the solutions are not unique, the sharp rollover in the curves indicates either a depth of complete local compensation of about 100 km (where the flexural rigidity approaches zero) or regional elastic support at shallower depths, with a flexural rigidity due to topographic loading of 10^{32} to 10^{33} dyne-cm. Each of these possibilities is discussed below.

Passive (isostatic) compensation at 100-km depth is possible only if this region is stable against creep deformation—that is, if lateral density variations providing compensation are statically maintained. An approximate temporal boundary between the elastic lithospheric behavior required for stable isostatic compensation and destabilizing viscous behavior is given by the Maxwell time, τ_M, the ratio of viscosity to elastic rigidity. Using 10^7 years as a geologically "young" reference age τ_0 and the temperature curves of Fig. 3, then for even the most creep-resistant geological material measured in the laboratory (23), τ_M is less than τ_0 for all depths greater than 50 km. That is, it does not seem possible to have passive compensation at 100 km unless the topography is geologically very young.

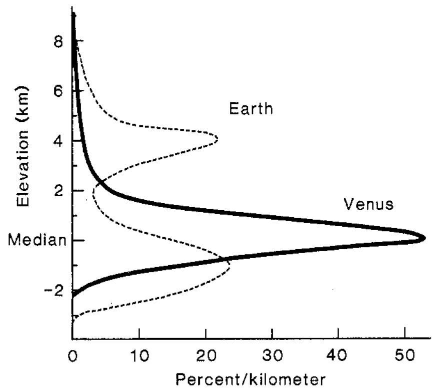


Fig. 2. Hypsometric curves of topography: frequencies of occurrence of elevations on Earth and Venus. Venus data are from (1).

The 50-km maximum lithospheric thickness corresponds to a flexural rigidity of 10^{31} dyne-cm, based on elastic rigidities typical of Earth's lithosphere. Thus the upper left-hand solution branch of Fig. 4, suggesting flexural rigidities in excess of 10^{32} dyne-cm, does not seem plausible.

On Earth the seismically determined flexural rigidities are in the same range, 10^{32} to 10^{33} dyne-cm, as the Venus loading estimates, and correspond to a range of old oceanic lithosphere (100 km) to continental lithosphere (200 km). It has been argued (24) that the zero-age loading and seismically determined flexural rigidities are the same and that the flexural rigidity determined from loading decreases with geologic time; possibly nowhere on earth is the observed (present age) loading value found to be greater than 10^{31} dyne-cm (and elastic lithospheric thickness greater than 50 km). Given venerean surface temperatures and Earth-like heat sources, it does not seem possible to generate loading flexural rigidities (and hence elastic lithospheric thicknesses) greater than Earth values [see also (25)].

A relative lack of volatiles in the venerean lithosphere might lead to sufficient creep resistance to more than offset the increased temperatures and allow substantially thicker lithospheres. The increased activation energy for creep would have to result from a lower water content than that of samples characterized as "dry" in laboratory experiments. [A "dry" rheology best matches the lower oceanic lithosphere (26).] However, the validity of the phenomenon of hydrolytic weakening in creep of basic igneous rocks, at least at temperatures well below those required for partial melting, is being questioned both theoretically and experimentally (27). In all, we do not believe there will be definitive implications regarding the volatile content of the venerean lithosphere until the role of hydrolytic weakening is better understood in the laboratory and Earth.

In summary, the results of the gravity analyses (Fig. 4) and the current understanding of creep laws for geologic materials suggest a dynamically maintained compensation of the venerean topography unless (i) all of the topography is exceedingly young geologically (younger than the Maxwell time for 100-km depth) or (ii) the generated heat (radioactive plus primordial) is considerably less in Venus than in Earth, leading to low, lunar-like temperature gradients. The latter appears unlikely on the basis of measurements of potassium, uranium, and thorium by the Venera spacecraft (28, 29) (Table 2).

A major compositional change at 115-km depth has profound implications if it is the crust-mantle boundary. If this interface (that is, the crust) is global, which is one interpretation of the strong (but not yet fully analyzed) gravity anomalies associated with all major topographic features, then Venus would have generated some seven times (normalized to planetary volume) more crust than Earth (oceanic plus continental). If only the upper mantle of Earth has been differentiated to form the oceanic and continental crust (30), it is not possible to differentiate even the entirety of Venus and produce an even remotely similar bulk composition of the venerean crust; alternatively, to produce a similar crustal composition for the two planets requires

Table 3. Spectral properties of gravity and topography.

Degree l	Venus $\sigma_l(g)$ (10^{-6})	Venus $\sigma_l(h)$ (km)	Venus $r_l(gh)$	Earth $\sigma_l(g)$ (10^{-6})	Earth $\sigma_l(h)$ (km)	Earth $r_l(gh)$
1		0.080			0.372	
2	1.72	0.100	0.41	2.55	0.224	−0.72
3	1.45	0.149	0.87	1.13	0.219	−0.10
4	0.86	0.111	0.17	0.51	0.186	0.46
5	0.45	0.078	0.01	0.33	0.162	−0.40
6	0.25	0.066	0.08	0.25	0.087	0.46
7		0.063		0.17	0.074	0.40
8		0.042		0.10	0.056	0.34
9		0.038		0.10	0.055	0.50
10		0.032		0.07	0.050	0.73
11		0.031		0.05	0.039	0.46
12		0.021		0.04	0.031	−0.11

significantly different whole-planet bulk compositions.

A more plausible alternative is that the compensation zone is not the crust-mantle boundary, but in fact represents regions of lateral heterogeneity in the mantle associated with convection and attendant surface disturbances. The density variations implied by the compensation could be compositional or thermal.

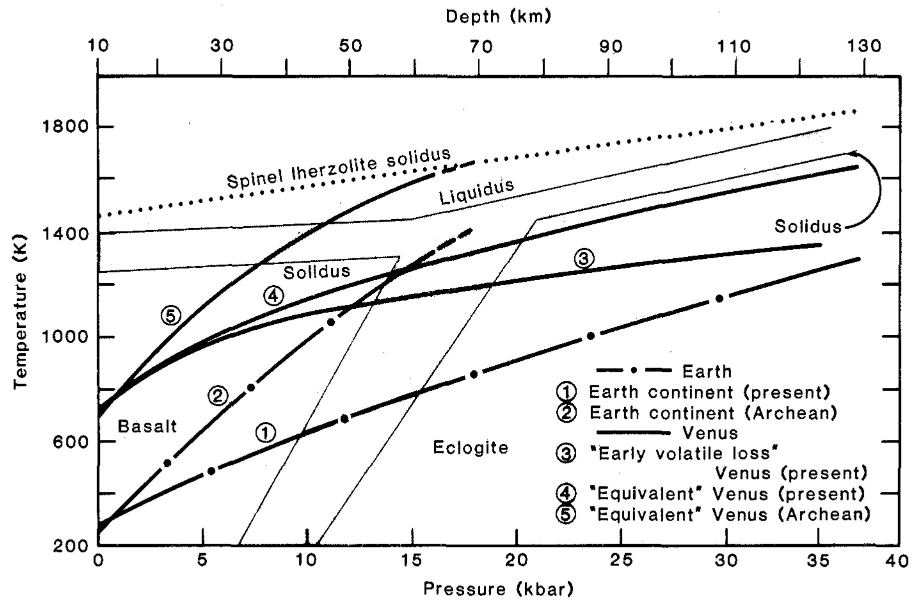


Fig. 3. Temperature curves for Earth and Venus now and in the Archean; calculated in 1-kbar steps taking into account the temperature and pressure dependence of conductivity. "Equivalent" Venus has crustal heat flux, 32 mW/m^2; mantle heat flux, 23.5 mW/m^2; decay depth of crustal radioactivity, 8 km; and crustal thickness, 30 km. The corresponding parameters for "early volatile loss" Venus are 35 mW/m^2, 11.6 mW/m^2, 16 km, and 60 km, respectively. In both cases, the volumetric heat generation at the surface is $\sim 4.1 \times 10^{-5}$ erg/cm^3-sec.

Global Morphology

In general, the terrain of the Median Plains appears to be rolling at the scale and resolution of Fig. 1. It is characterized by irregularly shaped, but roughly equidimensional, topographic features that vary in elevation from the median radius (6051.2 km) by about ± 0.5 to 1.0 km. These positive and negative features are about 500 to 1500 km in diameter.

Rising above this planetwide terrain are a few truly high areas. Two of these have elevations averaging several kilometers above the planetary meridian and are as large as small Earth continents. Terra Ishtar, centered at 70°N,10°E, is about the size of Australia; Aphrodite Terra, centered near 10°S,150°E, is about twice as large. The other elevated regions are much smaller than Ishtar and Aphrodite.

In Fig. 1 there appears to be a tendency for the elevated regions to be elongated and to be part of very long systems of elevations that roughly follow great circles. This tendency is best illustrated by Aphrodite, which lies along a trend oriented west-northwest to east-southeast that stretches over about 160° of longitude from 20°N,10°W (−10° in Fig. 1) to at least 20°S,150°E. Beta Regio, centered at 25°N,75°W, also appears to lie on this great circle, inclined roughly 30° to the equator. This elevated belt is referred to here as the Equatorial Highlands. East of Aphrodite is a complex of ridges and troughs (*1*) that seem to lie in the linear belt noted above, although the strike of individual features is not exactly parallel to this trend.

Ishtar extends beyond the northern limit of Pioneer Venus radar altimetry coverage. Hence its shape and total extent are uncertain. The known part appears to be elongated parallel to a trend that starts at about 65°N,130°E and is still going at the limit of coverage, near 73°N,60°W. Ishtar proper consists predominantly of a large plateau with a high massif, Maxwell Montes, rising above the eastern portion of the plateau and small massifs rising above its western margin (*31*). The Ishtar region (defined, as for Aphrodite, by the 1.5-km level) extends from about 65°N,80°E to 73°N,60°W. Although Maxwell Montes appears to have a large and roughly circular depression near its center that may be a caldera (*32*), the size, overall shape, and detailed structure of the massif indicated by radar reflectivity (*1*) make it unlikely that it is one large volcano. A topographic ridge parallels the arcuate and steep southwestern boundary of Ishtar (*33*). This ridge is separated by several hundred kilometers from the main mass of Ishtar and is the feature on Venus most similar in appearance to an island arc structure on Earth.

Although much smaller than Aphrodite or Ishtar, the elevated feature Beta Regio is of great interest because of its topography, as well as the basalt-like K, U, and Th abundances measured by the Venera 9 and 10 spacecraft landers (*28*). The crest in the southwestern part of Beta has been interpreted as a basaltic shield volcano in Earth-based radar reflectivity (*34*). A depression immediately to the east of this crest appears to be part of a chain of interconnected depressions defining a trough extending the full north-south length of Beta Regio and continuing southward to 17°S (*35*).

All the regions discussed in the preceding paragraphs are parts of major "linear" topographic trends on the surface of Venus; two are associated with large troughs, two provide some evidence that volcanism is at least partly responsible for their formation, and all are topographically elevated. Parallel lineaments near the equator at 10°E have also been noted (*36*). In total, there is evidence for horizontal stress in the lithosphere of Venus. Such stress distributions are essentially absent from the moon, are intimately associated with plate tectonics on Earth, and are associated with continental-style uplift and rifting, but not plate tectonics, on Mars (*9*).

In Fig. 5, we show several topographic profiles at right angles to the Aphrodite linear trend. Also shown are profiles across three different divergent plate boundaries [ocean rises (*37*)] on Earth, where the data have been smoothed and sampled to simulate Pioneer Venus altimetry characteristics. Specifically, the ocean rise profiles show a distinctly concave shape, which is a direct consequence of the conductively cooling, diverging oceanic lithosphere. This concavity is a fundamental feature and does not depend on material properties (other than thermal expansivity) or on the magnitude of steady plate velocity. Indeed, the differences in shape of the terrestrial profiles can be reconciled to a universal profile when time instead of distance is used as the *x* axis (*12*).

Although the terrestrial rises are often obscured by local topographic irregularities, the venerean profiles we have examined do not seem to show this concavity; if they possess any characteristic shape, it is convex. This absence of an ocean rise shape on the Venus profiles would be a fundamental argument against present-day terrestrial-style plate tectonics.

A more exhaustive analysis may be required to demonstrate a planetwide absence of terrestrial-type rises. What factors might obscure this simple negative observation? Because of the higher ambient surface temperature and lack of oceanic water pressure on Venus, the total conductive cooling and vertical relief of a compensated venerean rise could be less. Scaling the (typical) 2.8-km terrestrial relief to Venus, however, still yields a rise height of about 1 km, which is detectable by the Pioneer Venus altimetry. If much of the basalt produced at a divergent plate boundary occurred as surface flows, then the ratio of specific volume change to latent heat of freezing would lead to a larger volume change (per unit heat loss) than simple whole-rock cooling, and thus the characteristic concavity associated with a rise would probably be enhanced. The one factor that might easily obscure the characteristic rise profile would be rapid variations (episodic changes) in plate velocity, which in turn should lead to lack of a monotonic rise profile.

Earth-based radar showed large, rather circular, smooth features 20 to 1200 km in diameter on the Median Plains. Most are surrounded by an annulus of relatively rough terrain and hence look like impact craters (*38*). However, these features might be volcanic; their relative size distribution is not inconsistent with that origin, but the diameters of several of the features are larger than the largest known terrestrial caldera. Figure 6 shows Pioneer Venus altimetry profiles across some large circular features. Except possibly for structure D, they lack the topographic depressions suggestive of impact features. It is possible that the crater floors relaxed viscously over geologic time. Acceptance of this argument forces the conclusion that (i) the large-scale topography is young or dynamically supported or (ii) there was a significant change in rheology between the time the craters were formed and the time the topography was formed.

A crater interpretation for the circular features has profound implications for the evolution of Venus. It means that the plains—much of the surface of the planet—are geologically old. The frequency distribution of circular features greater than 75 km in diameter is 1.3×10^{-7} per square kilometer, corresponding to mean surface age of 1.7 ± 1.0 billion years (*39*).

Interpretation

Major uncertainties in interpreting the observations and modeling results are (i) the great geologic age of the plains, based on interpretation of the circular features as craters, and (ii) compositional inferences based on the Venera gamma-ray spectrometry: basalt associated with the Beta region and granite with the plains [a broad extrapolation of Venera 8 results (*29*)]. We keep these uncertainties in mind when developing alternative hypotheses.

It is likely that the Beta complex contains large basaltic shield volcanoes, based on the two Venera measurements and the geomorphic interpretations of the Earth-based radar data. A problem is the composition of other highland areas. From the apparent association of Beta in a global equatorial linear zone, it might be reasonable to assume that much of this zone contains basaltic volcanism. There is, however, no link with which to infer the composition of Ishtar. Linear zones of basaltic composition are reminiscent of terrestrial midocean ridges, as are parallel tectonic features such as those seen east of Aphrodite. Here the analogy becomes less certain, however, because of the apparent absence of a characteristic cross-sectional profile indicating conduction cooling. The tectonics of this zone may be more similar to continental swelling and rifting, such as found in Africa (*35*).

Acceptance of the "ancient surface" hypothesis rules out significant present-day crust generation by plate tectonics. It does not rule out ancient plate tectonics, with the plains as spreading crust and the Equatorial Highlands as the divergence zone. As the spreading became arrested, new basaltic crust would continue to pile up, creating the Equatorial Highlands. The gravity results imply that this tectonic system is still active—that is, the high-standing topography is quite young (hence few craters)—or that it is presently supported by mantle convection, which amounts to the same thing. The large region of surviving ancient crust suggests that active tectonism has been confined to certain geographic regions of Venus for a long time and is best characterized as "hot-spot dynamics." Many of the lineaments seen might be "gravity" or "load" tectonic in origin, although they could also be remnants of divergent plate boundary structure. If the granite-like composition of the plains is also accepted, ancient plate tectonism is not ruled out; in fact, these rocks offer a possible explanation for its cessation. If terrestrial continental material is formed dominantly through secondary differentiation processes at plate boundaries, then the wide extent of continental crust—the Median Plains—could have led to choking off plate tectonics. That is, the process was so efficient in creating continental material that eventually there was simply no open "oceanic" area in which to move about low-density continental crust.

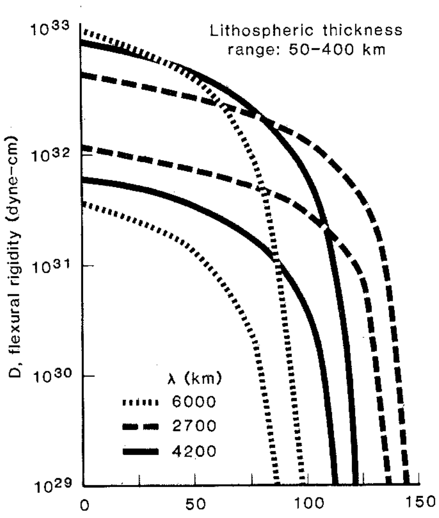


Fig. 4. Trade-offs of compensation depth, t_C, versus flexural rigidity, D, based on admittance estimates for three venerean topographic features at differing wavelengths.

If the ancient surface hypothesis is rejected, then the apparent lack of morphologic evidence for a cooling conduction boundary layer implies a very different tectonic style than on Earth, one much more regional and less global.

Ishtar is important in any tectonic hypothesis. It presents a steep front on its southern border and is plateau-like except for the superposition of Maxwell Montes, and an arcuate ridge stands off from and parallels the southwestern boundary (*33*). The topographic load of Ishtar (and possibly other high-standing regions on Venus) must, even with dynamic compensation, cause lithospheric stresses of several kilobars, and may require horizontal stress in the lithosphere for support. If Venus has become a one-plate planet, there should be considerable compression in its lithosphere, much more than on Earth (*40*). Several scenarios come to mind: (i) Ishtar was caused, and is supported, by stresses associated with a divergent but arrested or nascent plate boundary associated with the Equatorial Highlands. Compositionally, Ishtar is no different from the plains; it is an upthrown block of crust, and the steep southern border is a thrust boundary. (ii) Ishtar is the only true continent on Venus; it is granite-like and the plains are not (rejecting extrapolations from the Venera 8 data). Ishtar was formed as a consequence of terrestrial-type plate tectonics, and the ridge-like structure paralleling the southwestern boundary is an island arc. The divergent plate boundary is represented by the Equatorial Highlands, which at present do not actively spread, but supply sufficient horizontal stress to support Ishtar. Active volcanism along the Equatorial Highlands piles up new basaltic crust, with the major activity at Beta Regio and Aphrodite.

In summary, the present evidence suggests the absence of contemporary plate tectonics on Venus, but does not preclude plate tectonics in the past. Below, we explore factors that might have extinguished this style of tectonics had it existed.

Evolution: The Cessation of Plate Tectonics?

Two significant constraints on the formation of Venus are its great abundance of primordial argon (see Table 2) and its slow retrograde spin. Both properties suggest the plausible but nonunique hypothesis of impact by a major body. Such a "packaged delivery" may, however, be the only hypothesis proposed to date that can explain why Venus differs from Earth by a factor of 100 in primordial argon. As suggested by Wetherill (*41*), a body composed of material that had been heavily irradiated by close proximity to the early sun (within the orbit of Mercury) might explain this anomaly. The planetary rather than solar $^{20}Ne/^{36}Ar$ ratio in Table 2 would require that the same laws of isotopic discrimination apply in all parts of the nebula. While appeal to a fifth (and sixth, because of Earth's moon) former planet in the inner solar system may seem unaesthetic and ad hoc, it is a reasonable, but difficult to prove, outcome of growth of planets by planetesimal accretion (*42*).

An event that almost certainly occurred very early in the history of Venus was core formation; there is no reason to conjecture that Venus was any different from Earth and Mercury (*43*).

While nebula condensation models leave CO_2/H_2O ratios uncertain, the amount of CO_2 in Venus makes it plausible that the planet originally had sufficient H_2O for advanced differentiation to create granite-like rocks (Venera 8 measurement): an amount of H_2O somewhat less than is needed to create oceans. The dearth of H_2O in the venerean atmosphere (Table 2) attests to the instability of water at the surface in the present environment and implies an inability to recycle water to the interior, once outgassed. Hence, two major questions are the decay time for outgassing of volatiles and the epoch when the surface became hot enough to destabilize water.

If H_2O destabilization occurred in the second half of Venus' history, then Venus could have had an Archean like Earth's; that is, in the first 2 billion or 3 billion years outgassing of nearly all volatiles and formation of most of the volume of continental crust, but also appreciable recycling of crustal rocks, as energetically plausible and isotopically permissible. A problem that makes extrapolation to Venus difficult is the uncertainty about tectonic style during the terrestrial Archean. The petrology and trace element content of Archean rocks, as well as the configuration of greenstone belts, suggest a subduction-and-andesite regime similar to what has prevailed in more recent geologic time (*44*). However, nearly all present subduction is of oceanic lithosphere more than 30 million years old, and hence with a lithosphere-to-crust thickness ratio of more than 10 (*12*). The steeper Archean geotherm would have led to lower thickness ratios. Hence one would expect pileups of crustal material that, if the rate of differentiation of crust is proportionate to energy sources, would in a few hundred million years constitute a greater

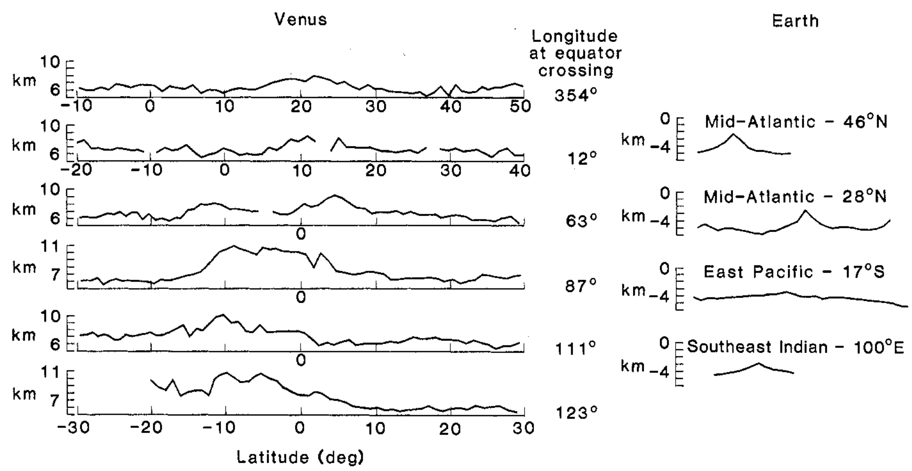
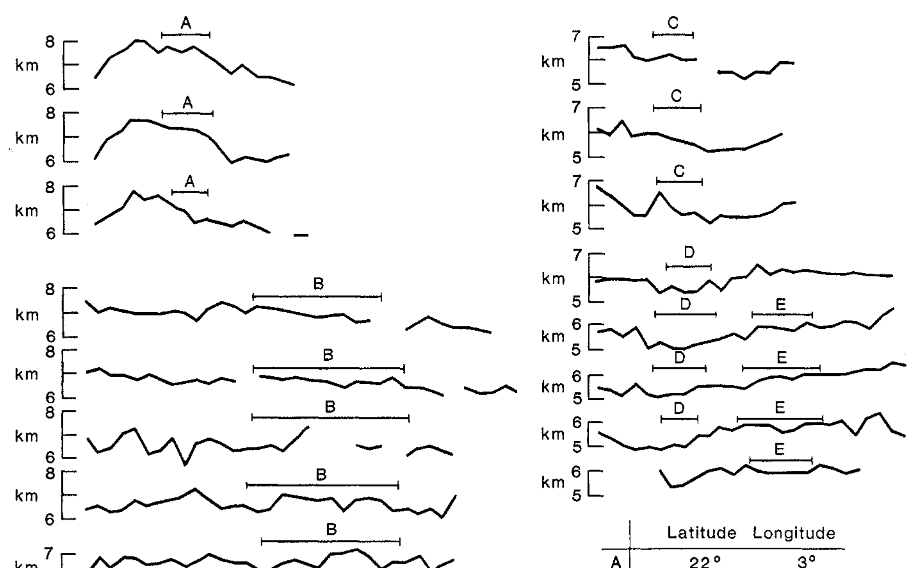


Fig. 5. Selected profiles at right angles to the linear trend of the Equatorial Highlands on Venus. Also shown, to the same scale, are selected profiles across ocean rises on Earth. Earth data have been degraded here to simulate the Pioneer Venus altimeter data characteristics.



	Latitude	Longitude
A	22°	3°
B	-26°	339°
C	18°	325°
D	21°	331°
E	29°	336°

Fig. 6. Locations of five large circular features (labeled A through E) identified in Arecibo radar images (*38*) shown in relation to Pioneer Venus altimetry profiles (*1*).

volume than is now observed in continental crust. Possibly the lack of crystallization ages greater than 3.8 billion years is the result of two factors: resetting of radioactive clocks by intense metamorphism (including the effects of impacts), and an ~ 0.8-billion-year time scale for reduction of the mean geotherm and evolution of lateral temperature inhomogeneities sufficient to stabilize "rockbergs" as cratons. At the next stage, temperature gradients could have dropped sufficiently for the basalt-eclogite transition to drive subduction. However, this scenario would still leave considerably more sialic material in the top 40 km than is now in Earth's crust; some thermomechanically plausible way of recycling this material is needed. In any case, it is plausible that the last third of Archean, 3.0 billion to 2.5 billion years ago, was a time of maximum stabilization of crust (as distinguished from differentiation) and that plate tectonics proper evolved in the Proterozoic (*44*).

These uncertainties in mechanisms for terrestrial evolution make it desirable to talk about Venus in terms of differences from Earth. We propose that two important factors would lead to the cessation of plate tectonics on Venus: loss of water from the interior and the higher surface temperature. Both tend to inhibit lithospheric subduction and the motion of continental blocks and to increase the rate of continent formation, with the latter leading to the choking up of the surface, as discussed in the previous section.

Loss of water from the interior may remove an asthenosphere, which could be important for developing terrestrial-style plate tectonics. On Earth, this mechanically weak region may uncouple the lithosphere from the underlying regions and provide ease of movement of the lithospheric layer. The role of trace amounts of water in lowering the temperature for partial melting close to or below the geotherm is probably the crucial ingredient in formation of the asthenosphere. The asthenosphere may persist despite volatile outgassing because of water storage in oceans and ultimate recycling to the interior by plate tectonic processes. Destabilization of water at the surface would interrupt this process and could lead to disappearance of the asthenosphere.

The present surface temperature on Venus is ~ 450°C higher than that on Earth. Several effects of this would lead to a less dense—hence more buoyant and difficult to subduct—lithosphere. First, the basalt-eclogite transition would be depressed on Venus (*45*) (Fig. 3), leading to a lithospheric column with lower density. Second, all other parameters being equal, the composition of basaltic magmas would be more magnesium-rich (higher Mg/Fe ratio) at elevated temperatures, and hence less dense.

If water destabilization on the surface of Venus occurred late (after the bulk of outgassing had taken place, so that the surface temperature was increased by a greenhouse effect) and an amount of continent comparable to that on Earth had evolved, then in any subsequent plate tectonic phase there would have been an appreciably greater ratio of material accreted to continents, rather than subducted, because of the lower negative buoyancy. At spreading rates comparable to Earth's, the entire surface could have choked up within a few tenths of a billion years. If destabilization occurred very early, before appreciable outgassing, then the production of granites would have ceased and subduction would be inhibited by loss of an asthenosphere, but the decrease in negative buoyancy due to the higher surface temperature would not have taken place until the remaining volatiles were outgassed. Another possibility is that all volatiles, including water, were lost very early. The question of volatile loss will probably not be settled, however, until the surface has been petrologically and geochemically sampled.

A phenomenon that may have occurred in connection with a rapid volatile loss and surface temperature rise is a reversal of the temperature gradient in the lithosphere (*10*). However, if this happened, it was almost certainly more than 1.0 billion years ago; hence it may have helped in the initial stabilization of plateau compensation, but would have little effect on the temperature gradient now.

After choke-up of the surface with crustal material, there would be a long period of tectonism of a planet as thermally active as Earth but with no active lithospheric spreading. On a regional basis (for instance, Beta Regio), there may be some analogy with Neogene Africa.

Conclusions

The apparent absence of any feature like an ocean rise and the positive correlation of gravity and topography at all wavelengths indicate that Venus is a one-plate planet, more like Mars than Earth. The sharpness of the unimodal peak in the topography suggests that this condition came about by the entire surface being choked up by continental crust, subduction being much more difficult than on Earth because of the dryness of the rocks and low density of the lithosphere.

A plausible scenario for Venus thus involves the following phases after accretion:

1) Major impact, bringing inert volatiles and creating the retrograde spin (after which any satellite would spin in by tidal friction);
2) Core formation;
3) Outgassing;
4) Crustal stabilization;
5) Plate tectonics;
6) Destabilization of water;
7) Choke-up of the surface by crustal material; and
8) One-plate tectonism.

One great uncertainty in this scenario is whether phases 6 and 7, destabilization of water and choke-up, occurred before or after the completion of phase 3, outgassing. Other problems include the elevation of the plateaus (as collision features of the choke-up phase or constructs of the past plate tectonic phase); the extent to which tectonism has dwindled; the manner of dynamic support of the highlands; and, underlying most of these, the efficiency of upward differentiation of radioactive heat sources.

Comparative consideration of the planets suggests that planets of the same size and mean density should follow roughly the same evolutionary path. The recently returned data about Venus directly challenge this premise. It is a delicately balanced set of the circumstances that determines the evolutionary style for any planet.

References and Notes

1. G. H. Pettengill, E. Eliason, P. G. Ford, G. B. Loriot, H. Masursky, G. E. McGill, *J. Geophys. Res.* **85**, 8261 (1980).
2. W. L. Sjogren, R. J. Phillips, P. W. Birkeland, R. N. Wimberly, *ibid.*, p. 8295.
3. C. T. Russell, R. C. Elphic, J. A. Slavin, *ibid.*, p. 8319; C. T. Russell, *Rev. Geophys. Space Phys.* **18**, 77 (1980).
4. J. H. Hoffman, R. R. Hodges, Jr., T. M. Donahue, M. B. McElroy, *J. Geophys. Res.* **85**, 7882 (1980).
5. V. I. Oyama, G. C. Carle, F. Woeller, J. B. Pollack, R. T. Reynolds, R. A. Craig, *ibid.*, p. 7891.
6. D. B. Campbell, B. A. Burns, V. Boriakoff, *Science* **204**, 1424 (1979); D. B. Campbell and B. A. Burns, *J. Geophys. Res.* **85**, 8271 (1980).
7. H. Masursky, W. M. Kaula, G. E. McGill, G. H. Pettengill, R. J. Phillips, C. T. Russell, G. Schubert, I. I. Shapiro, *Space Sci. Rev.* **20**, 431 (1977).
8. These coefficients are given by:

$$\sigma_l = \left[\sum_m \frac{\overline{C}_{lm}^2 + \overline{S}_{lm}^2}{(2l+1)} \right]^{1/2}$$

$$r_l = \sum_m \frac{\overline{C}_{lm}(g)\overline{C}_{lm}(h) + \overline{S}_{lm}(g)\overline{S}_{lm}(h)}{(2l+1)\,\sigma_l(g)\,\sigma_l(h)}$$

where $\overline{C}_{lm}$ and $\overline{S}_{lm}$ are coefficients for spherical harmonics normalized to give a mean square of unity and g and h refer to gravity and topography, respectively. The gravity coefficients are from M. P. Ananda, W. L. Sjogren, R. J.

Phillips, R. N. Wimberly, and B. G. Bills [*J. Geophys. Res.* **85**, 8303 (1980)]. We calculated the topography coefficients from Pioneer Venus altimetry data.
9. R. J. Phillips and K. Lambeck, *Rev. Geophys. Space Phys.* **18**, 27 (1980).
10. G. E. McGill, *Geophys. Res. Lett.* **6**, 739 (1979).
11. A. H. Lachenbruch, *J. Geophys. Res.* **75**, 3291 (1970).
12. J. G. Sclater, C. Jaupart, D. Galson, *Rev. Geophys. Space Phys.* **18**, 269 (1980).
13. E. Anders and T. Owen, *Science* **198**, 453 (1977); J. W. Morgan and E. Anders, *Geochim. Cosmochim. Acta* **43**, 1601 (1979).
14. N. H. Sleep, *J. Geol.* **87**, 671 (1979); N. T. Arndt, *Contrib. Mineral. Petrol* **64**, 205 (1977).
15. J. B. Pollack, *Icarus* **14**, 295 (1971); *ibid.* **37**, 479 (1979); J. C. G. Walker, *J. Atmos. Sci.* **32**, 1248 (1974).
16. D. J. Stevenson, G. Schubert, P. Cassen, *Lunar Planet. Sci.* **11**, 1091 (1980).
17. Isostasy, or the state of isostatic compensation, is usually defined as weight balancing of surface loads by subsurface density anomalies distributed in such a way that at some uniform depth the pressure is everywhere constant and below this depth the planet is in a state of hydrostatic equilibrium. As used in this article, isostasy is synonymous with "passive compensation" and implies stability against creep deformation. Dynamic compensation implies instability and thus maintenance by an active process such as convection. "Local compensation" means that the load is supported by the region directly below it, while "regional compensation" refers to support for a local surface load by a broad horizontal region of the interior. The type of regional compensation discussed most is elastic flexure of a lithospheric plate or shell.
18. J. R. Cochran and M. Talwani, *J. Geophys. Res.* **83**, 4907 (1978).
19. P. Molnar and P. Tapponnier, *ibid.*, p. 5361.
20. D. P. McKenzie and C. Bowin, *ibid.* **81**, 1903 (1976).
21. Admittance estimates were obtained by inverting the gravity data for surface density representations [in terms of radius, mass, and location of spherical disks; see W. L. Sjogren and J. C. Smith, *Proc. 7th Lunar Sci. Conf.* **3**, 2639 (1976)] and taking the ratio of the gravitationally derived mass to the actual topographic mass (assuming a density of 3.0). The dominant wavelength of the disk is determined by comparison of Taylor series expansions of the upward continuation of the gravity expressions for a disk and for a spherical harmonic wavelength. The equivalent wavelength is about π times the disk diameter.
22. The corresponding problem of the thin elastic plate is not appropriate because, at the wavelengths considered, spherical membrane stresses are nonnegligible. Unlike the thin elastic plate, the spherical solution depends on both D and t_L, with the dependence on the latter vanishing as the wavelength approaches zero. Using the results for deflection as a function of load [H. Kraus, *Thin Elastic Shells: An Introduction to the Theoretical Foundations and the Analysis of their Static and Dynamic Behavior* (Wiley, New York, 1967)], an expression for the spherical admittance function can be derived. Specifically,

$$Z = 1 + \frac{\Delta\rho}{\rho_c}\left(\frac{R_0 - t_C}{R_0}\right)^l \frac{\alpha_l}{1 + \alpha_l}$$

where ρ_c is the crustal density, $\Delta\rho$ the density contrast at depth t_C, R_0 the planetary radius, and

$$\alpha_l = \frac{c_1 f_l + c_2}{f_l^3 + 4f_l^2 + c_3 f_l + c_4}$$

where $c_1 = -\rho_c g_0 R_0^4/D$; $c_2 = c_1(1-\nu^2)$; $c_3 = c_{31} + c_{32} = \psi(1-\nu) + (\rho_c + \Delta\rho)g_0 R_0^4/D$; $c_4 = 2c_{31} + c_{32}(1-\nu)$; $f_l = -l(l+1)$; g_0 is planetary gravity; ν is Poisson's ratio; and $\psi = 12\ R_0^2/t_L^2$. The expression for Z_l can be inverted for D as a function of the observed Z_l, holding t_C and t_L as parameters to be varied.
23. R. L. Post, *Tectonophysics* **42**, 75 (1977).
24. C. Beaumont, *Geophys. J. R. Astron. Soc.* **55**, 471 (1978); A. B. Watts, J. H. Bodine, M. S. Steckler, *J. Geophys. Res.* **85**, 6369 (1980).
25. W. F. Brace and D. L. Kohlstedt, *J. Geophys. Res.* **85**, 6248 (1980).
26. C. Goetze and B. Evans, *Geophys. J. R. Astron. Soc.* **59**, 463 (1979).
27. T. E. Tullis, *Eos* **61**, 375 (1980).
28. Yu. A. Surkov, F. F. Kirnozov, V. N. Glazov, A. G. Duchenko, L. P. Tatsy, *Kosm. Issled.* **14**, 704 (1976).
29. A. P. Vinogradov, Y. A. Surkov, F. F. Kirnozov, *Icarus* **20**, 254 (1973).
30. R. K. O'Nions, N. M. Evensen, P. J. Hamilton, *J. Geophys. Res.* **84**, 6091 (1979).
31. G. H. Pettengill, P. G. Ford, W. E. Brown, W. M. Kaula, H. Masursky, E. Eliason, G. E. McGill, *Science* **205**, 90 (1979).
32. H. Masursky, E. Eliason, P. G. Ford, G. E. McGill, G. H. Pettengill, G. G. Schaber, G. Schubert, *J. Geophys. Res.* **85**, 8232 (1980).
33. M. C. Malin and P. R. Paluzzi, *Eos* **61**, 1019 (1980).
34. R. S. Saunders and M. C. Malin, *Geophys. Res. Lett.* **4**, 547 (1977).
35. G. E. McGill, *NASA Tech. Memo. TM 82385* (1980), p. 79.
36. M. C. Malin and R. S. Saunders, *Science* **196**, 987 (1977).
37. Terrestrial ocean rises form a continuous system 56,200 km long, average 3400 km in width, and have a mean depth of 2.6 km at the crest, dropping off to a mean depth of 5.5 km at crustal age 70 million years, or an average of 1700 km from the rise. Most of the shape of the lower modal peak of the histogram of Earth elevations (Fig. 2) is accounted for by the rises. This topographic drop-off is due to the oceanic lithosphere being the boundary layer for a global-scale convective system, which in turn shows that Earth has appreciable heat sources at depth.
38. D. B. Campbell and B. A. Burns, *J. Geophys. Res.* **85**, 8271 (1980).
39. W. K. Hartmann *et al.*, in *Basaltic Volcanism on the Terrestrial Planets* (Pergamon, New York, in press).
40. S. C. Solomon, *Geophys. Res. Lett.* **5**, 461 (1978).
41. G. W. Wetherill, *Lunar Planet. Sci.* **11**, 1239 (1980).
42. V. S. Safronov, *Evolution of the Protoplanetary Cloud and Formation of the Earth and Planets* (Technical Translation, National Aeronautics and Space Administration, Washington, D.C., 1972); G. W. Wetherill, *Proc. 6th Lunar Sci. Conf.* (1975), p. 1539.
43. S. C. Solomon, *Phys. Earth Planet. Inter.* **19**, 168 (1979); D. J. Stevenson, *Lunar Planet. Sci.* **11**, 1988 (1980).
44. R. B. Hargraves, *Science* **193**, 363 (1976); *Nature (London)* **276**, 459 (1968); D. P. McKenzie and N. Weiss, *Geophys. J. R. Astron. Soc.* **42**, 131 (1975); K. Burke and W. S. F. Kidd, *Nature (London)* **272**, 240 (1978); B. F. Windley, *The Evolving Continents* (Wiley, London, 1977); M. J. Bickle, *Earth Planet. Sci. Lett.* **40**, 301 (1978); S. R. Taylor, in *The Earth: Its Origin, Evolution and Structure*, M. W. McElhinney, Ed. (Academic Press, New York, 1979), p. 353.
45. D. L. Anderson, *Geophys. Res. Lett.* **7**, 101 (1980); A. E. Ringwood and D. L. Anderson, *Icarus* **30**, 243 (1977).
46. H. Jeffreys, *Mon. Not. R. Astron. Soc. Geophys. Suppl.* **4**, 62 (1937).
47. J. B. Pollack and D. C. Black, *Science* **205**, 56 (1979).
48. R. O. Pepin and P. Signer, *ibid.* **149**, 253 (1965); E. Mazor, D. Heymann, E. Anders, *Geochim. Cosmochim. Acta* **34**, 781 (1970).
49. This work was supported by NASA contracts NAS 2-9128, NASW 3389, NAS 2-9129, NAS 7-100, and NASGW-1. Lunar and Planetary Institute Contribution 424. We thank Kevin Burke, Norm Sleep, and Sean Solomon for useful criticism.