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Annular moats and outer rises around large Venus coronae such as Artemis, Latona, and Eithinoha are similar in arcuate planform and topography to the trenches and outer rises of terrestrial subduction zones. On Earth, trenches and outer rises are modeled as the flexural response of a thin elastic lithosphere to the bending moment of the subducted slab; this lithospheric flexure model also accounts for the trenches and outer rises outboard of the major coronae on Venus. Accordingly, it is proposed that retrograde lithospheric subduction may be occurring on the margins of the large Venus coronae while compensating back-arc extension is occurring in the expanding coronae interiors. Similar processes may be taking place at other deep arcuate trenches or chasmata on Venus such as those in the Dali-Diana chasmata area of eastern Aphrodite Terra.

It has been generally agreed since the exploration of Venus by the Pioneer Venus Orbiter that unlike Earth, there is no plate tectonics on Venus (*1*). In particular, the global system of mid-ocean ridges and the long-offset strike-slip faults that form the plate boundaries on Earth have no obvious counterparts on Venus. Data from the Venera (*2*) and Magellan (*3*) spacecraft confirm and strengthen these conclusions. Though there is no plate tectonics per se on Venus, recent Magellan radar images (*4*) and topographic profiles (*5*) of the planet suggest the occurrence of the plate tectonic processes of lithospheric subduction (*6*) and back-arc spreading (*7*). Much of this alleged tectonic activity occurs at large Venusian coronae which are circular to elliptical structures sometimes surrounded by an annulus of concentric fractures and a topographic moat; the interiors of most coronae are highly fractured and elevated with respect to the surrounding plains. The largest coronae, such as Latona, Artemis, and Eithinoha, resemble Earth subduction zones in both their planform and topographic profile. McKenzie *et al.* (*6*) compared the planform of arcuate structures in Eastern Aphrodite with subduction zones of the East Indies. The Venusian structures have radii of curvature that are similar to those of terrestrial subduction zones. Moreover, the topography of the Venusian ridge-trench structures is highly asymmetric with a ridge on the concave side and a trough on the convex side; Earth subduction zones generally display this same asymmetry. In this article, we present more quantitative comparisons between Earth subduction zones and the perimeters of the four major coronae. We then discuss the implications of subduction for corona evolution, mantle dynamics, and heat transfer.

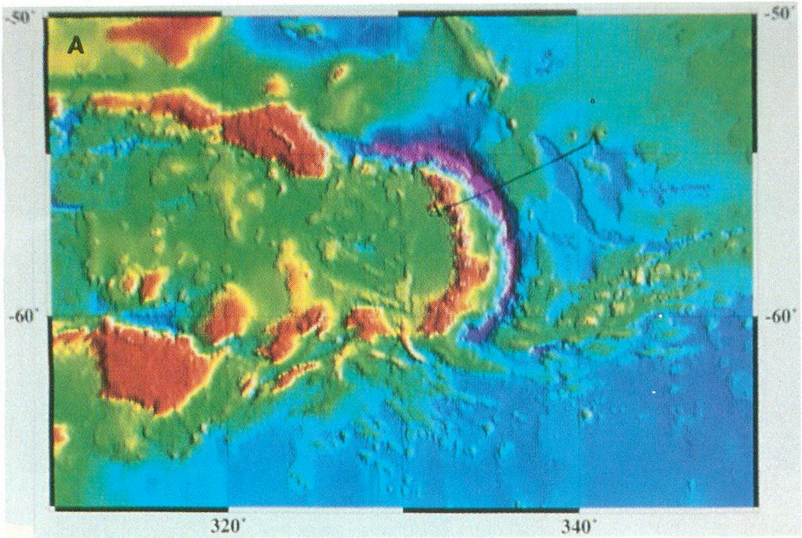
D. T. Sandwell is with the Scripps Institution of Oceanography, University of California at San Diego, La Jolla, CA 92093. G. Schubert is in the Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024.

Trench–outer rise topography and bending moment. Latona Corona (eastern Aphrodite, Venus) provides a striking resemblance to the South Sandwich trench (South Atlantic, Earth), as shown in Fig. 1. The Sandwich subduction zone is a deep arcuate trench having a radius of curvature of about 330 km. Inside of the trench axis lies an arcuate chain of tall volcanoes and islands. On Earth, this type of arc volcanism occurs when wet crustal rock along the upper surface of the subducted slab encounters hot mantle material at depths between 100 to 150 km (*8*). Wet rock has a melting temperature up to 400 K less than dry rock and thus the presence of island-arc volcanoes on the Earth implies that a significant amount of water is subducted.

A topographic profile across the Sandwich trench (A-A′ in Fig. 2) displays the characteristic trench–outer rise signature that is caused by downward flexure of the lithosphere (the mechanically strong outer shell of a planet) before subduction (*9*). We modeled this lithospheric flexure to determine the elastic plate thickness, the curvature of the plate, and the bending moment that is needed to support the topography of the outer rise. In general, a lithospheric flexure model consists of a thin elastic plate floating on a fluid mantle. A load is applied to deform the plate and gravity acts to resist the deformation; fiber stresses within the elastic plate smooth the deformation over a characteristic length scale. The length scale and the amplitude of the deformation provide estimates of the thickness of the elastic plate and the magnitude of the load, respectively. In the case of the Sandwich trench, we applied a bending moment to the free end of the plate and varied the plate thickness and the magnitude of the bending moment to fit the model topography to the observed topography (A-A′ in Fig. 2); the best fit model has a 40-km-thick plate. Like most other trenches on Earth, the extreme curvature of topography on the outer trench wall is sufficient to deform permanently the lithosphere before it is subducted (*10*). This inelastic behavior is marked by trench-parallel normal faults that extend from the trench axis to the outer rise.

Latona Corona displays essentially the same topographic and flexural characteristics seen at the Sandwich arc (Fig. 1B and profile B-B′ in Fig. 2). The deep arcuate trench along the southern margin of Latona has the same radius of curvature as the Sandwich trench (~340 km) and two tall arcuate ridges lie inboard of the trench axis. These ridges are significantly shorter and narrower than the island-arc volcanoes on Earth. Moreover, the arcuate ridges at Latona do not display the morphological characteristics of island-arc volcanoes and they do not appear to be sources of major lava flows. This lack of extensive back-arc volcanism at Latona may be due to the absence of water on Venus (*6*). The arcuate ridges at Latona may be tectonic expressions of either thermal-dynamic relaxation of the corona interior or active interior spreading that forces the rim to override the exterior lithosphere.

A topographic profile across the Latona trench (B-B′ in Fig. 2) displays the characteristic trench–outer rise signature associated with lithospheric flexure although it has an overall topographic amplitude that is somewhat less than at the Sandwich trench. Application of the flexure model to this profile, as well as 14 other profiles at Latona and many other profiles at three other coronae (Eithinoha, Heng-O, and Artemis), provides generally excellent fits to the observations (Table 1) (*7*). For profile B-B′ at Latona, a 30-km-thick elastic plate provides the best fit to the topography; this is similar to the 40-km-thick plate found for the Sandwich trench. The lower amplitude of the trench–outer rise at Latona relative to the Sandwich trench is to be expected because the lack of an ocean on Venus increases the gravitational restoring force by 1.4 times relative to that on Earth (*11*). Like most trenches on Earth, the extreme curvature of topography on the outer trench wall of the Latona trench is sufficient to deform permanently the lithosphere, perhaps in preparation for subduction. In addition, the SAR (synthetic aperture ra-



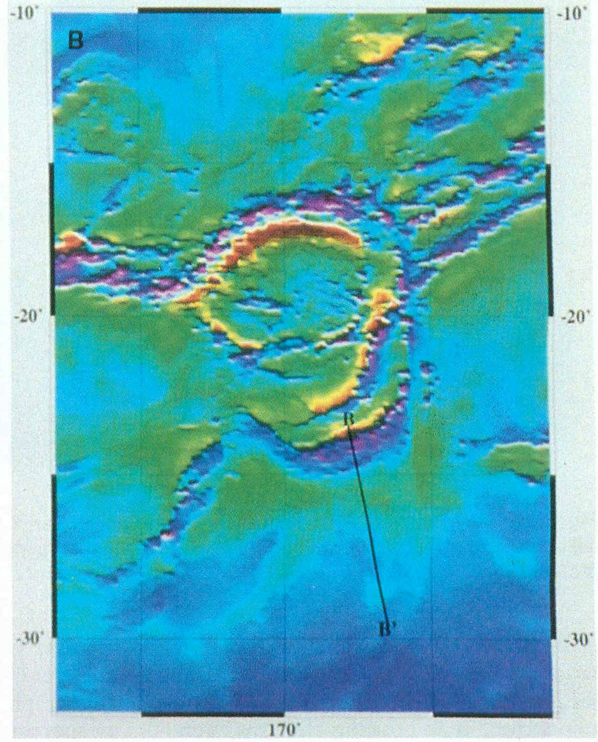


Fig. 1. (**A**) Seafloor topography of South Sandwich trench (South Atlantic, Earth) shows a tall volcanic ridge (inside arc, orange) and a deep ocean trench (outside arc, violet). Vertical descent of the South Atlantic lithosphere into the mantle has caused eastward migration of the trench axis and significant back-arc extension, which created the Scotia Plate during the past 36 million years. Currently, the back-arc spreading ridge is at 330° longitude. (**B**) Topography of Latona Corona (East Aphrodite, Venus) from Magellan altimetry (*5*), displayed at the same horizontal and vertical scale as the Sandwich trench (A) to emphasize the similarities between the two trenches. The southern arc displays a prominent ridge-trench–outer rise signature. The southernmost ridge is not massive enough to maintain the bending moment of the trench–outer rise flexure. Additional bending moment can be supplied by a subducted slab or by the second interior ridge.

dar) images of southern Latona display prominent trench-parallel faults or joints that extend from the trench axis to the crest of the outer rise, in agreement with the high tensile stresses predicted by the plate flexure model (*7*).

A second prominent example of a large radius trench–outer rise signature is found along the southern margin of Artemis Corona (Aphrodite Terra, Venus), which has a radius of curvature of about 1300 km (Fig. 3B). The Aleutian trench (North Pacific, Earth), having a somewhat larger radius of curvature (1900 km), was selected as a terrestrial analog (Fig. 3A). The major difference between these two structures is that the volcanic ridge inboard of the Aleutian trench is much taller and wider than the ridge inboard of the Artemis trench, a reflection of the extreme volcanic activity behind trenches on Earth. The topography of the trench and outer rise at Artemis is similar in both amplitude and wavelength to the Aleutian trench and outer rise, although the outer rise at Artemis is bowed upward; this bowing may reflect a large component of compression in a direction perpendicular to the trench axis (Fig. 4).

In addition to the above comparisons, we modeled the trench and outer rise topography of two other major coronae and five other Earth trenches (Table 1). A comparison between Eithinoha Corona and the Chile trench (Fig. 5) displays plate flexure of relatively thinner and weaker lithospheres (that is, lower saturation bending moment). The elastic thicknesses determined by modeling numerous profiles at Eithinoha, Heng-O, Artemis, and Latona are 15, 40, 35, and 37 km, respectively (*7*). Similar elastic thicknesses are found at the seven Earth trenches; the range in elastic thicknesses of the subducting oceanic lithosphere has been attributed to an increase in the thickness of the elastic layer as the plates cool with age (*9*). At Artemis and Latona, where the lithosphere appears to be yielding, the maximum bending moments are similar to those found at the Kuril and Aleutian trenches, respectively. These results suggest that the strength of the Venusian lithosphere is similar to the strength of terrestrial lithosphere despite the higher surface temperature of Venus.

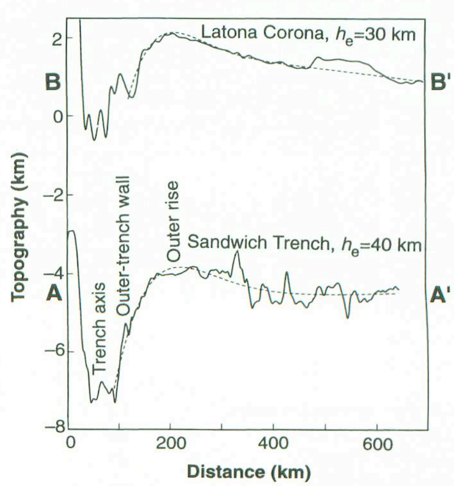
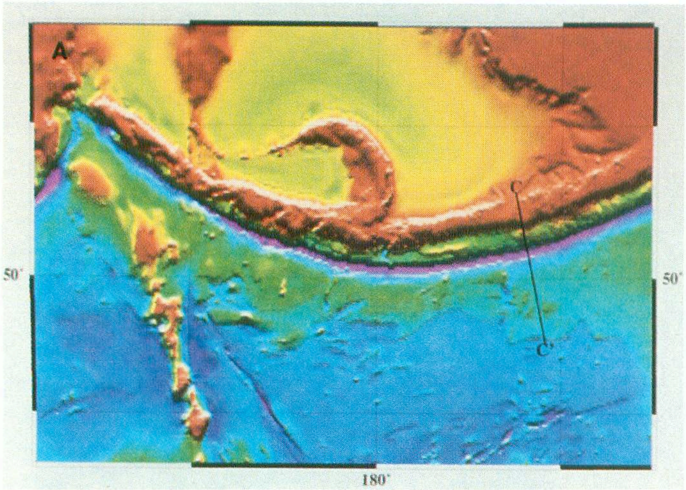


Fig. 2. Bathymetric profile A-A′ crossing the South Sandwich trench (Fig. 1A) displays the characteristic trench–outer rise signature associated with lithospheric flexure before subduction. The profiles are shown at 80 times vertical exaggeration, and thus the slope of the seafloor at the trench axis is less than 1°. An elastic plate model having an effective thickness of 40 km (dashed curve) provides the best fit to the profile. The intense curvature of the plate at the outer trench wall causes extensional failure in the upper 10 km of the lithosphere and ductile flow in the lower 10 km of the plate. Topographic profile B-B′ crossing Latona Corona (Fig. 1B) also displays a characteristic trench–outer rise flexural signature. An elastic plate model having a thickness of 30 km and a linear topographic gradient sloping away from the trench provides the best fit to the profile. The model of the yield strength envelope (*12*) predicts that there is 10 km of extensional failure in the upper lithosphere and 10 km of ductile flow on the bottom. Circumferential fractures on the outer trench wall and outer rise are evident in the SAR data (*7*).



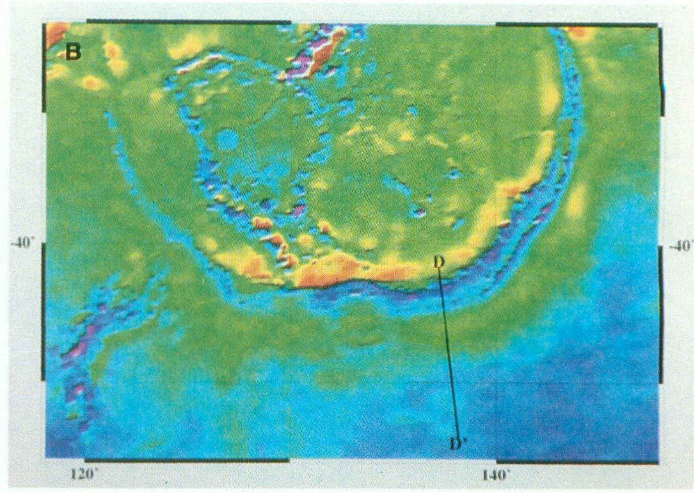


Fig. 3. (**A**) Bathymetry of Aleutian trench (North Pacific, Earth) showing a tall volcanic ridge (inside arc, orange) and a deep ocean trench (outside arc, violet). (**B**) Topography of Artemis Corona (East Aphrodite, Venus) from Magellan altimetry (*5*) displayed at the same horizontal and vertical scale as the Aleutian trench (A) to emphasize the similarities between the two trenches.

Because Venusian trenches display the major characteristics of Earth trenches and because Earth's lithosphere is known to be subducting, it is possible that the Venusian lithosphere is also subducting. We tested this hypothesis by determining whether the overriding coronal ridge is massive enough to supply the measured bending moments. If the ridge cannot supply the required moment, then one must invoke a negatively buoyant subducted slab to make up the deficit. Flexural modeling provides an estimate of the bending moment needed to support the outer rise topography (Table 1). We assume that the level where the flexural topography is zero, which is determined from the flexural modeling outboard of the trench, can be extrapolated to inside of the trench. Moreover, we assume that all topography $w(x)$ inside of the trench axis is supported by the underthrust plate so that there is no crustal thickening beneath the root to provide additional local support. For these assumptions, the maximum bending moment M_c that can be supplied by the coronal ridge is

$$M_c = \int_{-\infty}^{0} \Delta\rho \; g \; w(x) \; x \; dx$$

where x is the horizontal distance to the trench axis, $\Delta\rho$ is the density of the mantle, and g is the acceleration of gravity.

At Artemis, about two-thirds of the coronal ridge is needed to balance the bending moment of the trench and outer rise; all of this topography lies within 100 km of the trench axis. At Latona, however, the outermost coronal ridge (southernmost ridge in Fig. 1) is insufficient to balance the moment of the trench and rise; the second interior ridge must be included, but in this case most of this topographic moment lies more than 150 km from the trench axis. Because this distance is more than one-half of the flexural wavelength, it is likely that negatively buoyant subducted lithosphere supplies some additional moment. We performed the same calculation at the Sandwich trench and found that only about one-half of the volcanic arc is needed to balance the moment of the trench and outer rise. However, on Earth the downward force exerted by the topography of the volcanic arc is largely balanced by the upward buoyancy of its thick crustal roots (*8*), and the topographic moment does not support the moment of the trench and outer rise. The same isostatic compensation might occur on Venus. Thus, whereas the Venus moment balance calculation does not demonstrate the need for a negatively buoyant subducted slab, it cannot disprove the subduction hypothesis either.

Retrograde subduction around coronae. The observations and calculations discussed above can be explained by a model (sketched at the top of Fig. 6) in which the corona is essentially a hole in the lithosphere whose edge sags downward beneath its outer rim. Sinking and rollback (or retrograde migration) of the exterior lithosphere is accompanied by inflow of mantle material beneath the corona and extension of the corona interior (back-arc spreading). The interior extension occurs in a more distributed and

Table 1. Comparisons between flexural parameters derived from subduction zones on Earth and coronae on Venus. The thin elastic plate flexure model is used to estimate elastic thickness, plate curvature, and bending moment at the first zero crossing outboard of the trench axis. The elastic thickness and curvature values are used to estimate the mechanical thickness of the lithosphere on both Earth (*10*) and Venus (*12*). For Earth, only single topographic profiles were used to estimate flexural parameters whereas on Venus many profiles were used (*7*) (4 profiles for Eithinoha, 15 for Heng-O, 15 for Latona, and 12 for Artemis). On Earth both the mechanical thickness and bending moment increase as the lithosphere cools and thickens with age.

	Elastic thickness (km)	Curvature (10^{-8} m^{-1})	Mechanical thickness (km)	Bending moment (10^{16} N)	Age (Ma)
		Venus			
Eithinoha	15	29	20	0.9	
Heng-O	40	3	42	1.0	
Latona	35	29	50	6.1	
Artemis	37	103	74	25.4	
		Earth			
Middle America trench	12	58	14	0.6	25
Chile trench	20	70	27	3.2	40
Aleutian trench	30	50	39	7.8	65
Peru trench	40	26	46	9.4	40
Sandwich trench	40	49	59	18.3	75
Izu-Bonin trench	40	49	59	18.4	140
Kuril trench	45	42	72	22.5	130

disorganized way than the ridge-like spreading in terrestrial back-arc basins. The downward bending of the exterior lithosphere beneath the rim of the corona produces the trench or moat around the corona; the outer rise is an elastic flexural response to the downwarping.

The possible evolution of a large corona may proceed as follows (Fig. 6). Initially, the corona forms above a hot, upwelling mantle plume that has thinned and weakened the lithosphere (*13*) or along linear zones of distributed extension (*14*). Massive surface volcanism, from pressure-release melting in the upwelling mantle (stage 1), eventually causes the lithosphere to break (stage 2). Once the lithosphere has broken, the edges of the thick lithosphere can sink because of their negative buoyancy; this process produces a trench that migrates retrograde into the surrounding lithosphere (stage 3). The exterior lithosphere need not roll back everywhere or simultaneously around the entire corona. The downwarped lithosphere may be torn (or segmented) in the radial direction, and local force balances can determine which lithospheric segments peel back and subduct into the surrounding lithosphere. The interior of the corona expands in this final stage, and mantle material rises passively (or actively) to fill the void. Active upwelling into the corona can assist the rollback of the trench by supplying a radially outward pressure force against the exterior lithosphere. The regional topographic gradients at Artemis, Latona, and Eithinoha coronae are downhill in the direction of possible trench migration; this topographic pressure gradient may also assist the rollback of the lithosphere.

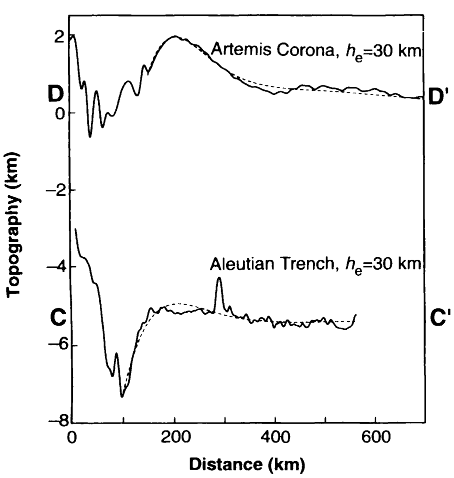


Fig. 4. Bathymetric profile C-C′ crossing the Aleutian trench (Fig. 3A) displays the characteristic trench–outer rise signature associated with lithospheric flexure before subduction. An elastic plate model having an effective thickness of 30 km provides the best fit to the profile (dashed curve). Topographic profile D-D′ crossing Artemis Corona (Fig. 3B) also displays a characteristic trench–outer rise flexural signature. An elastic plate model having a thickness of 30 km and a linear topographic gradient sloping away from the trench provides the best fit to the profile. The extensive outer rise at Artemis may indicate that the lithosphere is under extreme horizontal compression.

This concept of lithospheric foundering, trench rollback, and back-arc extension was developed to explain the geometries and kinematics of many subduction zones on Earth. A good example of this type of retrograde subduction is the Sandwich trench (Fig. 1A) where the trench axis has migrated more than 1100 km in an easterly direction during the past 36 million years (*15*). The lithosphere behind the Sandwich trench consists of relatively young seafloor formed by a series of back-arc spreading ridges; currently, the spreading ridge is located at 300°E longitude. The topography and tectonics of this back-arc region are poorly organized in comparison with normal seafloor spreading ridges.

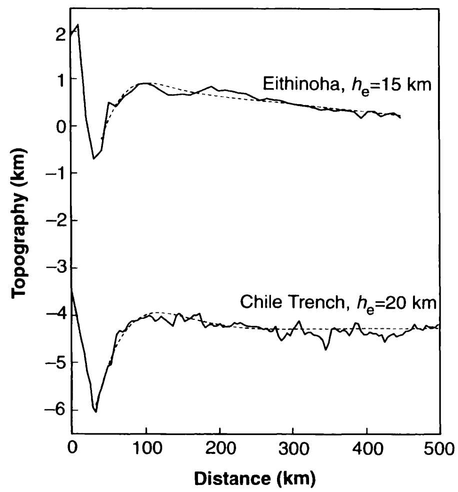
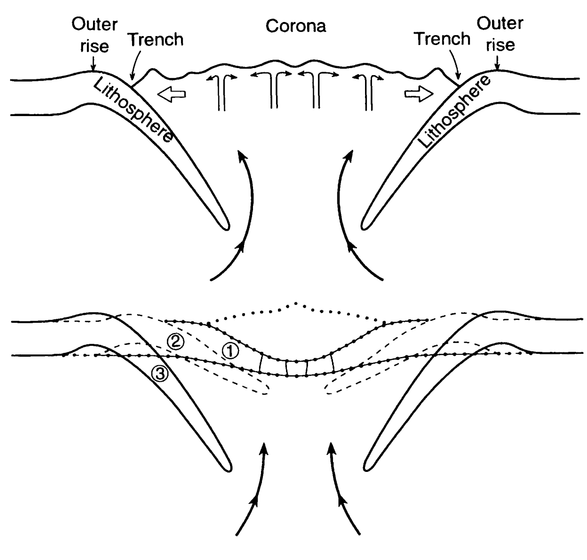


Fig. 5. Topographic profiles across the northwest rim of Eithinoha Corona (15-km-thick elastic plate) and the Chile trench (15-km-thick elastic plate) display the lower amplitude and shorter wavelength flexures associated with a thinner lithosphere. On Earth, variations in lithospheric thickness are proportional to the square root of the lithospheric age (*9*).

Implications for Venus tectonics. The flexural character of the topography of the trench and outer rise on the margins of large coronae is strong evidence that the lithosphere exterior to the coronae is warped downward beneath the coronae interiors. However, it is not required that this downwarping represents retrograde subduction; the interiors of the coronae may simply be overthrusting the exterior lithosphere (Fig. 6, stage 1). Our analysis of the bending moment required to support the trench and outer rise topography indicates that the ridge, inward of the trench, can supply the moment in the case of Artemis but not in the case of Latona unless a second inner ridge, far from the trench axis, is included. In the case of the terrestrial subduction zones, isostatic support of the inner volcanic ridge precludes the ridges from exerting a torque on the descending slab. A similar situation may apply on Venus, and thus high-resolution (~300-km wavelength) gravity anomaly measurements will be required to distinguish between overthrusting (uncompensated ridge) and retrograde subduction (Airy-compensated ridge). Adequate gravity data may be obtained by the Magellan orbiter.

Subduction of Venus lithosphere requires that it be negatively buoyant with respect to the surrounding mantle. The buoyancy of the Venus lithosphere de-

Fig. 6. (**Top**) Proposed schematic cross section of lithospheric subduction around a mature and major corona (radius >~300 km). (**Bottom**) Possible evolution of a large corona; the corona forms (stage 1) above a hot upwelling mantle plume that causes massive surface volcanism and thinning and weakening of the lithosphere. Weakening and the volcanic load (stage 2) eventually cause the lithosphere to break. Once the lithosphere has broken (stage 3), the edges can sink because of their negative buoyancy. This produces a trench that migrates retrograde into the surrounding lithosphere.



pends on the thickness of the imbedded crust and the thickness of the lithosphere, which in turn depend on the rate of temperature increase with depth as well as the rheology of the lithosphere (*16*). All of these quantities are highly uncertain for Venus, although when reasonable values are adopted the Venusian lithosphere should remain positively buoyant (*16*). Densification of the crust by phase changes from basalt to garnet granulite and eclogite may be needed to facilitate subduction on Venus. In that case the lithosphere exterior to the corona might have to be underthrust to a depth of about 100 km before retrograde subduction could take place. This process could explain why only the largest coronae on Venus show evidence for retrograde subduction; most coronae on Venus are probably too small (*17*) to underthrust the surrounding lithosphere to sufficient depths to initiate subduction.

Our model of retrograde subduction on the margins of large coronae is consistent with the hypothesis that coronae form above hot mantle upflows or plumes (*13,17*). The hot upflow is required to thin (and perhaps break) the lithosphere, to provide the volcanic load through pressure release melting, and to downwarp the lithosphere sufficiently to initiate subduction. If the plume head is buoyant and large, it may exert a radially directed pressure force on the margins of the corona that actively assists the retrograde migration of the trench. This outward-directed pressure might give rise to compressional deformation in the trench and surrounding lithosphere.

The occurrence of retrograde subduction on Venus is consistent with our understanding from fluid dynamics (*18*) that convection in a largely internally heated mantle should be dominated by downwelling instabilities from the cold upper thermal boundary layer (lithosphere). Thus, we propose that the same physical process that drives plate tectonics on Earth is also important in the tectonics of Venus even though the lithosphere subduction forces on Venus do not apparently result in a completely analogous plate-like tectonic configuration.

On Earth, the mantle is mainly cooled by the cold subducting lithosphere (*18*). Lithospheric subduction on Venus should play a similar role in cooling the mantle because Venus is about the same size and composition as Earth. We can evaluate the potential importance of subduction on Venus to planetary heat transfer by estimating the total length of subduction zones on Venus (*19*) and comparing with the total length of terrestrial subduction zones [37,000 km (*20*)]. Retrograde subduction on Venus may be occurring not only at the marginal trenches of the large coronae Artemis, Latona, and Eithinoha, but also at arcuate trenches such as Dali and Diana chasmata in eastern Aphrodite Terra (6) and elsewhere on the planet, such as Hecate Chasma, Hestia Rupes, Nightingale Corona, and Parga Chasma. The total length of these arcuate trenches is 15,000 km (*21*). [The estimate would be greater if features such as Quetzalpetlatl Corona and the margins of plateau highlands such as Western Ishtar Terra and Thetis Regiones (*22*) were included.] Of course we do not know if any of these features are currently subducting. If we assume that they are all active and have terrestrial convergence rates, this trench-length estimate indicates that mantle cooling by lithospheric subduction is a potentially important process on Venus. A more complete study is required.

Also relevant to considerations of planetary heat flow on Venus are the elastic thicknesses implied by our flexural modeling of the topography of the trenches and outer rises around the large coronae. Such large elastic thicknesses suggest that surface heat flow is quite low (one-third to one-fourth of the mean terrestrial surface heat flow). Unexpected low heat flow, at least in some areas of Venus, requires revisions to our thinking about the near-surface thermomechanical structure of the planet.

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21. The following features were identified in a gridded Venus topography map (*5*) as possible subduction zones on the basis of their ridge-trench–outer rise topography and arcuate planform: Artemis Corona, Latona Corona, Eithinoha Corona, Nightingale Corona, Dali Chasma, Diana Chasma, Hecate Chasma, Parga Chasma, Hestia Rupes, and a number of unnamed arcuate features. There are many other more subtle trench-like expressions that would almost double the estimated trench length of 15,000 km.
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23. We thank P. Ford for providing an updated version of the altimeter profiles and many technicians at Jet Propulsion Laboratory for processing of the SAR images. D. McKenzie was the first to notice that many large-scale features of eastern Aphrodite Terra resemble subduction zones on Earth. He also proposed that the absence of back-arc volcanoes on Venus was due to the lack of water. The research was partially supported by the Magellan Project (JPL 958950 and JPL 958496).