where $J = 3NuK/a^2$, $\gamma = \alpha gV/C_p$, t is time, t_0 is total ascent time, $Nu = 0.8Pe^{1/2}$, $Pe = Va/K$, Pe is the Peclet number, V is the velocity of magmatic ascent, a is the body radius, $K(=1 \times 10^{-6}\,m^2s^{-1})$ is the thermal diffusivity, $\alpha (=6 \times 10^{-5}\,deg^{-1})$ is the coefficient of thermal expansion, g is the gravitational acceleration, and $C_p(=1.25 \times 10^{-4}$ ergs $Kg^{-1}K^{-1})$ is specific heat capacity. T is the mean magma temperature, T_0 is the magma temperature in the source region, and n is a constant that defines the shape of the planetary thermal gradient (equation (1)). Equation (2) reduces to the expression for the thermal gradient (equation (1)) for an infinitely slow ascent (dimensionless ascent time $Jt_0 = \infty$), and to the adiabatic curve $T/T_0 = e^{-\gamma t}$ for an infinitely fast ascent ($Jt_0 = 0$). A typical plot of the resulting cooling curves for terrestrial conditions, contoured in Jt_0 values, is illustrated in Fig. 1. In order for the magma to reach the surface unsolidified, the cooling curve must not cross the solidus before it reaches the surface. The allowable Jt_0 values obtained from the cooling curve plots for Venus and Earth can be directly compared to obtain relative minimum magma ascent velocities, source depths, and body sizes. The results are shown in Fig. 2.

The cooling model for the buoyant crack ascent has previously been described briefly in [2]. It is the problem of a magma at an initial temperature T_0 placed in contact with the wall rock of temperature T_m. This problem was initially solved by [7], and their solution for the average temperature T as a function of time is

$$\frac{T - T_m}{T_0 - T_m} = \frac{8}{\pi^2} \sum_{m=1}^{\infty} \frac{\exp\{-(2m-1)^2 \pi^2 Kt/4a^2\}}{(2m-1)^2} \tag{3}$$

where the notation is the same as in equation (2), and the right side is constant for any single dimensionless ascent time (Kt/a^2). This result is for a constant wall rock temperature, but can be adapted to a variable wall rock (thermal gradient) temperature by approximating an incremental magma ascent in a simple numerical scheme where the initial magma temperature T_0 at any location m is, instead of the source depth temperature, the final magma temperature at the previous location $m-1$ [2]. If heat is conducted ahead of the magma body, the boundary temperature of the magma and wall rock will not be constant ($T_{contact} = T_m$) at any given location, but will be the average of the two initial temperatures of the magma and wall rock

at any location for the majority of the cooling time [8]. For this case, the contact temperature at the mth position is the average of the final temperature of the magma at the $m-1$ position (T_{m-1}) and the initial wall rock temperature at the mth position (T_{m0}). The preliminary results from this model indicate that the effect of the planetary thermal structure is of the same order of the effect seen in the pluton model.

In general, for both ascent mechanism models presented here, the influence of the planetary thermal structure parameters for Venus in the probable order of decreasing importance is surface temperature, surface temperature gradient, thermal gradient curvature with depth, and planetary mantle temperature. The higher surface temperature of Venus, for otherwise similar planetary thermal structures, allows considerably smaller minimum possible crack sizes and/or magma body sizes, and slower ascent velocities than would be possible on Earth for a reasonable range of Venus source depths and surface thermal gradients. This surface temperature effect is greater for more primitive magma compositions, and may be greater for magmas of higher crystallinity. A higher venusian surface thermal gradient has the same effect of the higher surface temperature on magma transport, but to a much lesser degree. Similarly, for higher values of thermal gradient curvature with depth (higher n in equation (1)), the minimum possible ascent velocity and body/crack size also decreases slightly. If the mantle temperature for Venus is elevated by a hundred degrees or so over that of Earth [9], it should result in a modest increase of melt production and magma transport to the surface compared to Earth. The effect of the range of Venus surface temperatures with elevation ($390°-470°C$ or $660°-740°K$ [10]) is under investigation, and is also anticipated to have a significant effect on magma transport, possibly greater than that of the higher mantle temperature.

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EVIDENCE FOR RETROGRADE LITHOSPHERIC SUBDUCTION ON VENUS.

David T. Sandwell[1] and Gerald Schubert[2], [1]Scripps Institution of Oceanography, La Jolla CA 92093, USA, [2]Department of Earth and Space Sciences, University of California, Los Angeles CA 90024, USA.

Though there is no plate tectonics per se on Venus [1], recent Magellan radar images [2] and topographic profiles [3] of the planet suggest the occurrence of the plate tectonic processes of lithospheric subduction [4] and back-arc spreading [5]. The perimeters of several large coronae (e.g., Latona, Artemis, and Eithinoha) resemble Earth subduction zones in both their planform and topographic profile. McKenzie et al. [4] have 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.
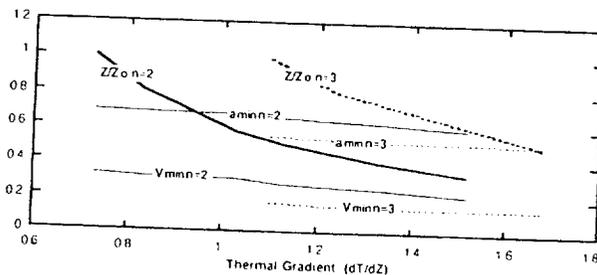

Fig. 2. Plot of the results for basaltic pluton ascent on Venus. The results are nondimensionalized by the corresponding terrestrial values, and the source depth values are the direct result of the assumed planetary thermal structure (equation (1)). For example, for a Venus thermal gradient the same as the terrestrial thermal gradient and $n = 2$, the corresponding minimum source depth is about 60% of the terrestrial value the minimum ascent velocity is about 30% of Earth's and the minimum body size is about 70% of Earth's. Thermal structure parameters: $n = 2$; $dT/dZ = 1.0$ (dT/dZ of Earth); $Z_0 = 1.0$ (Z_0 of Earth).

Trench/Outer Rise Topography: 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. A topographic profile across the Sandwich trench (A–A') displays the characteristic trench/outer rise signature that is caused by downward flexure of the lithosphere prior to subduction [6]. We have 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; the best-fit model has a 40-km-thick plate. Like most other trenches on the Earth, the extreme curvature of topography on the outer trench wall is sufficient to permanently deform the lithosphere prior to subduction [7]. This inelastic behavior is marked by trench-parallel normal faults extending from the trench axis to the outer rise.

Latona Corona displays essentially the same topographic and flexural characteristics seen at the Sandwich arc (Figs. 2 and 3). The deep arcuate trench along the southern margin of Latona has the
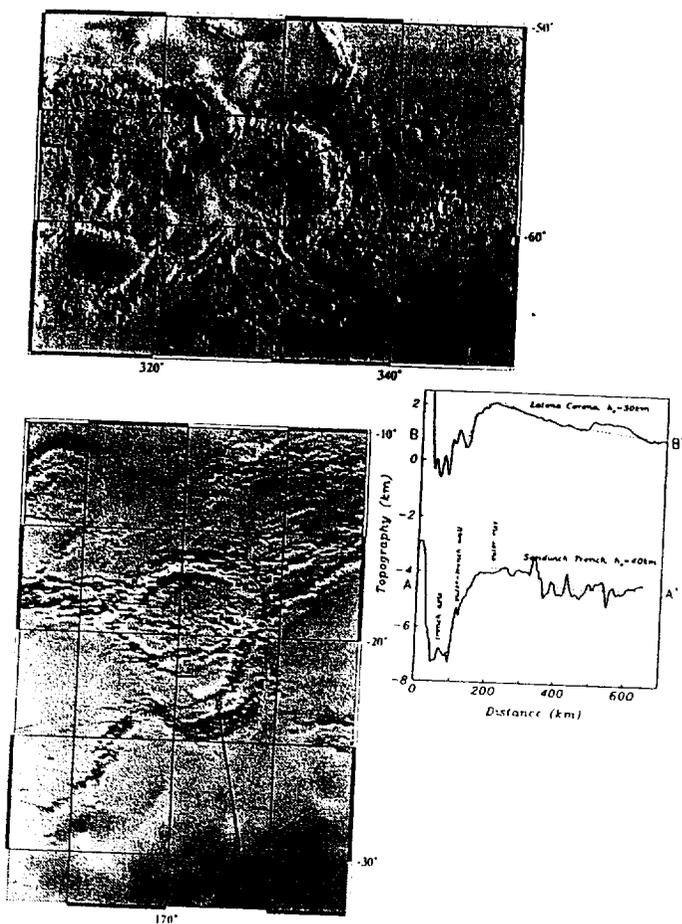

same radius of curvature as the Sandwich trench (340 km) and inboard of the trench axis lie two tall arcuate ridges. A topographic profile across the Latona trench (Fig. 3) displays the characteristic trench/outer rise signature associated with lithospheric flexure although its overall amplitude is somewhat less than at the Sandwich trench. As in the case of the Sandwich trench, we applied the flexure model to the trench/outer rise topography at Latona and estimated an elastic plate thickness of 30 km, which is similar to the elastic thickness at the Sandwich trench. Like trenches on the Earth, the outer trench wall of the Latona trench has a high curvature, suggesting that the plate is flexed beyond its elastic limit, perhaps in preparation for subduction. SAR images display prominent circumferential fractures on the outer trench wall in agreement with the plate flexure model [5].

Since venusian trenches display the major characteristics of Earth trenches and since the Earth's lithosphere is known to be subducting, it is possible that the venusian lithosphere is also subducting. We have 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. At Artemis, about two-thirds of the coronal ridge is needed to balance the trench/outer rise bending moment; all of this topography lies within 100 km of the trench axis. At Latona, however, the outermost coronal ridge (southernmost ridge in Fig. 2) is insufficient to balance the trench/outer rise moment; 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 (i.e. more than one-half of the flexural wavelength). 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 trench/outer rise moment. However, on the Earth, the downward force exerted by the topography of the volcanic arc is largely balanced by the upward buoyancy of its thick crustal roots and the topographic moment does not support the trench/outer rise moment. The same isostatic compensation might occur on Venus. Thus, while 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: These observations and calculations can be explained by a model of lithospheric foundering, trench rollback, and back-arc extension that was developed to explain the geometries and kinematics of many subduction zones on Earth including the Sandwich Trench. The corona is essentially a hole in the lithosphere whose edges sag 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 disorganized way than the ridgelike 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 occurrence of retrograde subduction on Venus is consistent with our understanding from fluid dynamics [8] 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

Fig. 1. (Top image) Bathymetry of South Sandwich Trench (Earth) as a tall volcanic ridge, a deep ocean trench, and the characteristic trench/outer rise signature associated with lithospheric flexure prior to subduction (A–A'). (Bottom image) Topography of Latona Corona (East Aphrodite, Venus) at the same horizontal and vertical scale as the Sandwich Trench (top). The southern arc displays a prominent ridge-trench-outer rise signature (B–B'). The south-ernmost 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.

not apparently result in a completely analogous platelike tectonic configuration.

On Earth, the mantle is mainly cooled by the cold subducting lithosphere [8]. Lithospheric subduction on Venus should play a similar role in cooling the mantle. We can evaluate the potential importance of subduction on Venus to planetary heat transfer by estimating the total length of subduction zones on Venus [9] and comparing it with the total length of terrestrial subduction zones (37,000 km [10]). 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 [4] and elsewhere on the planet (e.g., Hecate Chasma, Hestia Rupes, Nightingale Corona, and Parga Chasma). The total length of these arcuate trenches is about 15,000 km [11]. 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 [12] were included. Of course, we do not know if any of these features are presently active. Assuming 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.

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OVERVIEW OF VENUS GEOLOGY: PRELIMINARY DE-SCRIPTION OF TERRAIN UNITS FOR VENUS GLOBAL GEOLOGIC MAPPING.   R. Stephen Saunders, Ellen R. Stofan, Jeffrey J. Plaut, and Gregory A. Michaels, Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109, USA.

Venus terrain units can be categorized on the basis of morphology, reflectivity, backscatter, roughness, and emissivity. Morphology can be inferred from Magellan left-looking nominal incidence angle image mosaics, right-looking coverage, and more limited left-looking stereo. The typical resolution is about 300 m down to about 120 m near periapsis in the cycle one nominal coverage. The scale of geologic mapping governs definition of mappable terrain units. Initial global mapping is being compiled at a scale of 1:50 million. At this scale, the smallest individual features that can be mapped is about 125 km. The categories of terrain types are plains, complex ridge terrain, features with morphology suggesting volcanic or

volcano-tectonic origin, features interpreted to be tectonic in origin, crater units, and surficial units such as splotches and streaks. The following are brief descriptions of terrain units that are being mapped globally at the 1:50 million scale.

Plains:

Smooth plains—Planar surfaces with low radar backscatter and smooth texture.

Smooth plains with wrinkle ridges—Plains with widely spaced (10 km or more) linear to sinuous ridges.

Mottled plains—Plains with many apparently overlapping lobate outline subunits creating a light and dark mottled appearance.

Gridded plains and lineated plains—One or more crossing sets of parallel radar bright lineaments cross the plains.

Complex ridge terrain (CRT):

CRT1—Single trend of generally parallel but irregular ridges and troughs of various wavelengths from a few kilometers to tens of kilometers; individual ridges may exceed 50 km in length.

CRT2—CRT1 disrupted by sets of crosscutting lineaments; Morphology varies from long, sinuous ridge sets to blocky.

CRT3—Two prominent sets of ridges and troughs that are approximately orthogonal; relatively short ridges (25 km) and longer disrupting linear zones (50 km).

CRT4—Chaotic arrangement of ridges and troughs intersecting at a variety of angles and scales; may have lensate or hummocky appearance.

Morphology suggesting volcanic and volcano-tectonic origin:

Corona—Annular arrangement of ridges and troughs; interior varies.

Arachnoid—Circular to quasicircular features with radial systems of lineaments.

Shield—Low h/w often with radial flow-like patterns; diameter 50 to several hundred kilometers.

Dome—Small shield structure with steep sides and broad convex or concave summit; generally simple circular in plan.

Dome field—Cluster of approximately one hundred or more 3- to 10-km dome forms.

Scalloped dome—Dome with radial ridges separating scoop or theater-shaped grooves. Many have surrounding landslide debris.

Flow field—Complex of individual lobate flow-like features typically with parallel alignments and common source.

Channel—Sinuous trough or sinuous linear contrasting pattern on plains.

Features interpreted to be tectonic in origin:

Linear troughs and bright lineaments resembling graben or fractures—Generally steep-sided straight troughs and bright lineaments interpreted to be graben faults and fractures.

Lineament zone—Bands of linear features and broad troughs and basins.

Ridges—Positive linear features similar to lunar wrinkle ridges.

Ridge belts—Bands of ridges having a generally common trend.

Crater units—Various crater related features including ejecta, flow material and pababolic halos.

Splotch—Dark and bright quasicircular features.

Windstreak—Bright and dark streaks generally terminating at one end at a topographic feature such as a dome or ridge.