will help to make more specific predictions that can be tested with observations of the style and distribution of volcanism. In addition, Monte Carlo simulations of the interaction of impact cratering and volcanic processes in the production and evolution of the Venus crust [17] will provide data that can then be compared to observations in order to further distinguish between models for the resurfacing history of Venus.

Finally, we have information on only about the last 20% or less of the history of Venus as presently observed in the surface record. Assessment of thermal evolution models for the first 80% of the geological and volcanological history of Venus may provide an important context for the presently observed record.

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CHEMICAL DIFFERENTIATION ON ONE-PLATE PLANETS: PREDICTIONS AND GEOLOGIC OBSERVATIONS FOR VENUS. J. W. Head, E. M. Parmentier, and P. C. Hess, Department of Geological Sciences, Brown University, Providence RI 02912, USA.

Recent studies have examined the partial melting of planetary interiors on one-plate planets and the implications for the formation and evolution of basaltic crust and the complementary residual mantle layer [1–3]. In contrast to the Earth, where the crust and residual layer move laterally and are returned to the interior following subduction, one-plate planets such as Venus are characterized by *vertical* accretion of the crust and residual layer. The residual mantle layer is depleted and compositionally buoyant, being less dense than undepleted mantle due to its reduced Fe/Mg and dense Al-bearing minerals; its melting temperature is also increased. As the crust and depleted mantle layer grow vertically during the thermal evolution of the planet, several stages develop [2,3]. As a step in the investigation and testing of these theoretical treatments of crustal development on Venus, we investigate the predictions deriving from two of these stages (a stable thick crust and depleted layer, and a thick unstable depleted layer) and compare these to geologic and geophysical observations, speculating on how these might be interpreted in the context of the vertical crustal accretion models. In each case we conclude with an outline of further tests and observations of these models.

Implications of the Presence of a Stationary Thick Depleted Mantle Layer: In this scenario (Fig. 1), the crust has thickened to several tens of kilometers (less than the depth of the basalt/eclogite transition) and overlies a thick depleted mantle layer.

Volcanism. Rates of surface extrusion should have decreased with time due to evolving thermal gradient and increase in depleted layer thickness and should be low. Present rates of volcanism on Venus are apparently low (<0.5 km^3/a), comparable to terrestrial

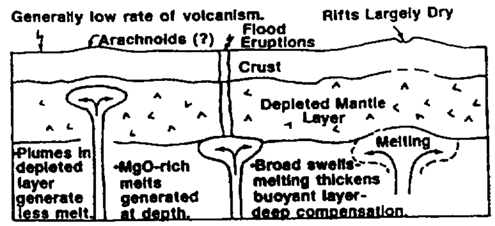

Fig. 1. Stationary thick depleted mantle layer.

intraplate volcanism rates [4]. For plumes, if conditions were comparable on Venus and Earth, the higher lithospheric temperature on Venus caused by the higher surface temperature would result in plumes ascending to shallower depths, and greater pressure-release and lithospheric melting there [5]. In the scenario described here (Fig. 2), plumes ascending from depth would not penetrate to shallow depths and thus should undergo less pressure-release melting and less melting and incorporation of a cooler and depleted mantle layer. Although volcanism is associated with many features interpreted to be plumes on Venus (shield volcanos and many coronae), there is a wide range of other features (arachnoids and numerous coronae) that show minimal signs of volcanism [4,6]. This could be consistent with the presence of a thick depleted layer. Another implication of the presence of the thick depleted layer is that plumes undergoing pressure-release melting at the depth of the base of this layer (Fig. 1) will produce MgO-rich melts that should yield very voluminous, low-viscosity surface flows [7]. This could be consistent with the abundant large-volume and apparently fluid lava flows and sinuous rillelike features observed in the Magellan data [4,8]. Another consequence of the presence of a thick depleted layer is that volcanism should be concentrated in regions above the largest upwellings (Fig. 2). This could be consistent with the observation that much of the volcanic activity (particularly edifices and structures) on Venus is associated with large rises such as Beta, Atla, and Themis, and the adjacent regions [4,9,10].

Tectonics. A stable depleted mantle layer will enhance lithospheric buoyancy and will inhibit the development of crustal spreading and plate tectonics. In addition, rifting may commonly be unaccompanied by volcanism ("dry"), except in extreme cases. This could be consistent with the lack of presently observed crustal spreading on Venus [11] and the general paucity of volcanism associated with rift zones except locally in regions of broad rises [10].

Crustal/upper mantle structure. On Venus, the apparent depth of compensation of many regional-scale features is much greater than on Earth [12]. If density variations in a viscous mantle are the cause of these features, a low-viscosity zone in the upper mantle

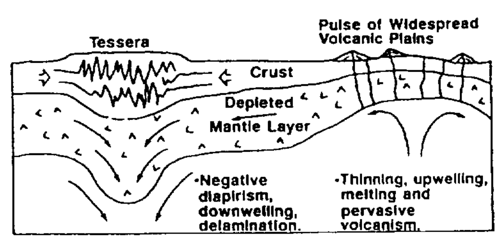

Fig. 2. Instabilities that develop in a depleted layer.

caused by mantle material approaching its melting temperature, as it does on Earth, would be highly improbable on Venus. The colder, thicker depleted mantle layer with a higher melting temperature than normal mantle would inhibit and perhaps preclude partial melting and the development of a low-viscosity zone. Thus, the great apparent depths of compensation could be related to the presence of a thick depleted layer. Regions of deepest compensation on Venus (e.g., Beta Regio) are characterized by broad rises and associated rifting and centers of volcanism and are thought to represent the surface expression of mantle plumes [10]. If these plumes penetrated to the bottom of the depleted layer, melting would locally thicken the buoyant layer, and this greater thickness of low-density mantle may support the broad surface topography. Thus, in this scenario, the apparent depth of compensation may reflect the thickness of the depleted layer.

Implications of Instabilities Developing in a Thick Depleted Mantle Layer: As it thickens and cools, the depleted mantle layer may become unstable (for example, tradeoffs between compositional and thermal buoyancy related to general planetary cooling can result in net negative buoyancy for the depleted layer [2,3]). In these cases, the depleted layer will mix into the convecting interior, the base of the thermal boundary layer and melting rise to shallow depths, large amounts of melting occur, contributing again to the growth of the crust (with voluminous and widespread volcanism) and the complementary depleted mantle layer. Some of the predicted consequences of such a period of instability (Fig. 2) would be negative diapirs, delamination, upwelling, massive pressure-release melting, and a period of widespread volcanic flooding and resurfacing. These events would be short term, and separated in time by long periods of crustal buildup (Fig. 1) to the next instability event.

Volcanism. Such a scenario may be consistent with volcanological implications of many aspects of the crater population. The impact crater population cannot be distinguished from a completely spatially random population [13], and this can be interpreted to mean that it is in production and is superposed on a substrate that was produced over a very short period of time about 500 m.y. ago and that has been only locally modified by volcanism since [14]. In this scenario, the cratered surface of Venus was completely resurfaced by volcanic deposits to a depth of at least 10 km in a very short period of time [14], erasing all previous craters. This thickness (10 km) corresponds to the creation of 0.46×10^{10} km^3 of volcanic deposits, a rate of about 46 km^3/a if the event took place over 100 m.y., and 460 km^3/a if it took place over 10 m.y. The latter value is equivalent to a global layer 1 mm thick per year. This new surface then begins to accumulate a production crater population during which there is a much decreased rate of volcanism. The very small number of craters that have been clearly modified by volcanism is cited as supporting this scenario [14].

Tectonism. In the process of development and evolution of instabilities in the depleted layer, crustal shortening, thickening, and surface deformation is likely to occur (Fig. 2). The scales and styles will be related to the scale of the instabilities and the rheology of the crust and depleted mantle material. We consider the possibility that the tessera regions represent relict sites of downwelling associated with such instabilities. Tesserae show crater densities comparable to the rest of Venus [13,14], are highly deformed [15,16], represent regions of thickened crust [17], make up between 10% and 20% of the planet [16], and often have borders suggesting deformation and underthrusting [15,16]. These borders often extend for many hundreds to thousands of kilometers, indicating that the underthrusting events were large scale [16]. In addition, some areas, like Western Ishtar Terra, are ringed by distinctive mountain ranges of compressional origin, suggesting large-scale downwelling there [18]. Thus, these regions could be linked to large-scale downwelling events associated with depleted-layer instabilities. Two scenarios for instabilities and surface deformation and volcanism seem plausible. In one, the residual layer becomes negatively buoyant and diapirism is widespread, but the diapirs are not closely coupled with the uppermost mantle and crust, and surface deformation is limited and localized to the region above the negative diapir. In this scenario, fertile mantle material would flow in to replace the lost diapir region and pressure-release melting at depths previously occupied by the depleted layer would cause extensive regional volcanism. Resurfacing would take place focused on these regional centers of diapirism. In another scenario, coupling of the negative instability and the upper mantle and crust would be more complete, and an instability would cause large-scale crustal downwelling and thickening, lateral thinning of the crust and depleted layer in distal regions (Fig. 2), and the possibility of rifting and the initiation of crustal spreading to create new crust in these regions. During this process, the models suggest that crustal recycling is taking place; one challenge is to identify places in the geologic record where this might have taken place (e.g., Ishtar Terra). Crustal spreading could be a major part of the renewal process, with old crust being thickened, deformed, underthrust, and possibly subducted over regions of downwelling, and crustal thinning, large-scale pressure-release melting, and crustal spreading occurring over the complementary regions of the planet. Modest crustal spreading rates (similar to those on the Earth, e.g., ~5 cm/a) for a total ridge length equivalent to a planetary circumference could result in creation of new crust for between one-third and one-half of the planet in 100 m.y. Further analysis of the scale of development of instabilities and the implication of rates and thermal structure for uppermost mantle and crustal coupling are required to develop these scenarios to the point that they can be tested with observations.

Implications of Vertical Crustal Accretion for the Geological History of Venus: A range of parameters has been explored for these models and different conditions can result in variations in the thickness of the crust and the depleted layer [2,3]; however, several themes emerge as characteristic of all models and might be thought of as predicted consequences of vertical crustal accretion on a one-plate planet. These include:

1. *Early stability.* Early period of history where crust and depleted layer are growing and are broadly stable. This period may be marked by the loss of crustal material from the base of the crust and by convective mixing of the base of the depleted mantle layer.

2. *Decrease of surface volcanism as a function of time.* This results from the secular cooling of the interior but is enhanced by the growth of the depleted layer.

3. *Onset of instability.* Midway through the history of Venus, an initial instability develops in the depleted layer, causing major crustal modification and resurfacing.

4. *Cyclical nature of instabilities.* Following the initial instability event, the models predict that the growth and destruction of the depleted layer will take place at 300–500-m.y. intervals. The surface of Venus as presently observed is less than a billion years old [13,14], and there is no evidence of more ancient heavily cratered terrain. The large volume of crust predicted by thermal evolution models suggests that some mechanisms of crustal loss must have operated on Venus in its past history [19]; these models provide a mechanism for the initial buildup as well as subsequent removal and renewal of crustal material.

Further Development and Tests of these Scenarios: No one observation can be shown to uniquely confirm these models and scenarios, but many of the features predicted by the models are consistent with the observed characteristics of Venus geology and geophysics. These models therefore merit further consideration. Some of the things that are required to permit the further analysis and testing of these scenarios include (1) Better definition of the growth, stability, and style of renewal of the crust and depleted layer, and the relation to lithosphere evolution. (2) Analysis of the scale and nature of instability: Is it characterized by catastrophic surface turnover and crustal spreading, or deeper negative diapirs and resurfacing of a relatively stable and intact veneer? (3) Do the heavily deformed tesserae show patterns consistent with the initiation and subsequent deformation during the period of instability? (4) If crustal spreading has taken place as part of the resurfacing process, what geometries and rates are compatible with the cratering record? (5) How fast does resurfacing have to be to be consistent with the crater record? Is this reasonable from turnover and magma generation point of view?

Crustal formation processes have been characterized as primary (resulting from accretional heating), secondary (resulting from partial melting of planetary mantles), and tertiary (resulting from reprocessing of secondary crust [20]. Venus appears to represent a laboratory for the study of vertical accretion of secondary crust, which may have important implications for the earliest history of the Earth.

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DYNAMICS OF THE VENUS ATMOSPHERE. A. P. Ingersoll, California Institute of Technology, Pasadena CA 91125, USA.

The superrotation of the Venus atmosphere is a major unanswered problem in planetary science [1]. At cloud-top levels (65–70 km altitude) the atmosphere rotates with a five-day period, corresponding to an equatorial wind speed of 90 m/s [2–4]. Angular velocity is roughly constant on spherical shells, and decreases linearly with altitude to zero at the surface. The direction of rotation is the same as that of the solid planet, which is retrograde—opposite to the direction of orbital motion, but the 5-day period is short compared to the 243-day spin period of the solid planet or to the mean solar day, which is 117 Earth-days at the surface.

The problem with the superrotation is that shearing stresses tend to transfer angular momentum downward, and would slow the atmosphere until it is spinning with the solid planet. Some organized circulation pattern is counteracting this tendency, but the pattern has not been identified. A simple Hadley-type circulation cannot do it because such a circulation is zonally symmetric and Hide's theorem [5] states that in an axisymmetric circulation an extremum in angular momentum per unit mass M can exist only at the surface. Venus violates the last condition, having a maximum of retrograde M on the equator at 70–80 km altitude. This leaves waves and eddies to maintain the superrotation, but the length scales and forcing mechanisms for these motions need to be specified.

The wind speed at cloud-top level is proportional to the equator-to-pole temperature difference through a relation known as the thermal wind equation [1]. The magnitude of the temperature difference reflects a balance between radiative forcing, which tends to warm the equator and cool the pole, and poleward heat transport by atmospheric motions—including the same waves and eddies that are maintaining the superrotation. The great mass and large heat-carrying capacity of the lower atmosphere limits the temperature gradient there. The temperature difference at cloud-top level is of order 30 K [1]. If the circulation were more efficient at all altitudes, the temperature difference would be smaller and the superrotation would be weaker. Understanding the superrotation is equivalent to understanding the equator-to-pole temperature distribution, and neither are understood at present.

The mean meridional wind at cloud-top level is poleward in both hemispheres, according to cloud-tracked wind analysis from 1974 to 1990 [2–4]. The zonal wind varied from 80 to 100 m/s during the same period. Both the eddies and the symmetric circulation are tending to remove angular momentum from the equator at cloud-top levels [2,3], thereby adding to the load that other waves and eddies must carry. The most visible global feature is the Y, a dark marking centered on the equator that looks like the letter Y rotated counterclockwise by 90°. Its four-day period is significantly shorter than that of small-scale markings that drift with the flow, so it is probably a Kelvin wave with zonal wavenumber equal to one [6,7]. On Earth, the eastward-propagating Kelvin waves and the westward-propagating Rossby-gravity waves alternate in driving the winds of the equatorial stratosphere to the east and west, respectively, in a cycle known as the quasibiennial oscillation (QBO). The waves are presumably driven by convection in the troposphere, but the exact nature of their excitation is not yet fully understood [5]. The role of these waves on Venus, how they are excited, and why they do not produce larger swings in the equatorial zonal wind are still unanswered questions. Convection occurs in two altitude ranges on Venus: from the surface to about 30 km altitude, and within the clouds from 49 to 55 km altitude [1]. It is possible that small-scale convective motions randomly excite the large-scale Kelvin wave, which carries retrograde momentum upward and maintains the superrotation.

Tides are the other major class of atmospheric motions that could be maintaining the superrotation [8–10]. They are the atmosphere's linear response to daily heating by the Sun. Both the heating and the response are global in scale and are phase-locked to the Sun as the atmosphere rotates beneath it. Tides propagate vertically, away from the altitudes where solar heat is absorbed. On Venus this heating is located near the tops of the clouds. The propagating waves carry energy and momentum away from this layer and could lead to a net retrograde acceleration. Tides are seen in the Venus images [2,3,6] and temperature data [11], and many of the observed features are reproduced in the models. The problems center around the distribution of tidal heating, the dissipation of tidal energy, the relation between tides and convection, which also has a diurnal component, and the role of the deep atmosphere, which is difficult