200 km. The apparent depth of compensation appears to shallow from about 200 km at 7°S to close to 100 km at about 10°N. Preliminary mapping of this region (image C1-MIDRP.00N095;1) indicates complex terrain, dominated by tessera, and represents the northern slope of Aphrodite Terra where elevations drop to around mpr or lower. We interpret this region to be a zone of rapidly changing crustal thickness, resulting in a relatively shallow apparent depth of compensation. Five impact craters have been mapped in this region, perhaps suggesting that this may be a region of relatively old crust.

At approximately 20°N, the observed and predicted los gravity anomalies are roughly anticorrelated, a low in the observed gravity corresponding to highs in the predicted gravity for compensation depths of both 100 and 200 km. Much of this region is below an elevation of –1 km relative to mpr, and the relatively dense subsurface predicted by the isostatic models is clearly in error. Subsurface densities appear to be less dense than expected in this region, suggesting flexural or more likely dynamic control of this low topography. Coronae and fractured volcanic features dominate this region.

From approximately 30°N to 60°N the observed and predicted los gravity anomalies are in reasonable agreement, and there is clearly little resolution of the apparent depths of compensation in this region as there is little difference among the anomalies predicted for 100- and 200-km compensation depths. This region is mostly lowland plains at an elevation of -0.5 ± 0.5 km relative to mpr. Major terrain differences between this region and the region immediately to the south, where observed and predicted gravity are very poorly correlated, are not readily apparent in the Magellan images.

Preliminary mapping of geological features on Magellan images along the path of Pioneer Venus orbit 440 do not indicate a first-order correlation among surface features and changes in the apparent depth of compensation of los gravity data. The apparent depth of compensation appears to be most variable in regions dominated by tessera, but not all areas of tessera have distinct gravity signatures. There is a weak correlation among areas in which impact craters are relatively common and areas in which the observed and predicted gravity anomalies are poorly correlated.

Acknowledgments: Gerry Schaber and the staff of the U.S. Geological Survey are thanked for their assistance in making the Magellan images available to us.

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N93-14323

VENUS VOLCANISM: A GLOBAL OVERVIEW FROM MAGELLAN DATA. J. W. Head[1], L. S. Crumpler[1], J. C. Aubele[1], and the Magellan Team, [1]Department of Geological Sciences, Brown University, Providence RI 02912, USA.

A preliminary analysis of a global survey of Magellan data covering over 90% of the surface and designed to document the characteristics, location, and dimensions of all major volcanic features on Venus has revealed over 1660 landforms and deposits [1]. These include over 550 shield fields (concentrations of small volcanos <20 km in diameter), 274 intermediate volcanos between 20 and 100 km diameter with a variety of morphologies, 156 large volcanos in excess of 100 km diameter, 86 calderalike structures independent of those associated with shield volcanos and typically 60–80 km in diameter, 175 coronae (annulus of concentric ridges or fractures), 259 arachnoids (inner concentric and outer radial network pattern of fractures and ridges), 50 novae (focused radial fractures forming stellate patterns), and 53 lava flood-type flow fields and 50 sinuous lava channels (all of which are in excess of 10^2–10^3 km in length).

The near-global coverage of Magellan data analyzed in this study confirms and extends the results of earlier observations [2] that showed that volcanism is a widespread and significant process on the surface of Venus for the period of time in the presently observed record (less than about the last one billion years [3,4]). Volcanic units comprise in excess of 80% of the surface of the planet, and indeed the remainder of the planet largely consists of tessera, which itself may be deformed lava flows. The minimal influence of erosion on the surface results in the stunning preservation of the wide array of volcanic features and edifices documented in this study. The high-resolution and global coverage of the Magellan image data has provided the opportunity for the global inventory [1]. On the basis of the characteristics of the landforms and deposits, the vast majority of the units appear to be of basaltic composition, consistent with the results of the earlier Venera landers [5]. However, important morphologic variations suggest a wider range of lava compositions on the surface, consistent with a range of petrogenetic environments [6]. For example, the morphology of the steep-sided domes and festoons [7,8] suggests that they may represent more viscous magmas with more evolved compositions. Long sinuous rilles and channels may indicate the location of sites of extrusion of ultramafic or other very fluid magmas [9]. The large lava floods indicate that effusions comparable to terrestrial flood basalts were a relatively common occurrence on Venus. In addition, the array of features that have associated volcanism strongly suggest that volcanism is related to a wide variety of scales of mantle upwelling, from hot-spot-like plumes of about 200 km diameter [10] to much larger several thousand-kilometer-diameter broad rises such as Beta and Atla Regiones [11]. Similarly, the variations in surface morphology and amount of associated volcanism of many of these features strongly suggest that there is a wide range of intrusive and extrusive processes operating, including the largely intrusive aspects of arachnoids, the radial dikelike patterns associated with novae [10,12], and the predominantly extrusive large volcanos. Indeed, there is some evidence that there may be an evolutionary sequence of features beginning with novae, extending through large volcanos, and ending in coronae. Evidence also exists for large calderas, coronae, and other features that indicate that many magma reservoirs may be relatively large on Venus compared to Earth. One of the major outstanding questions in Venus volcanology is the nature of the melting process, the evolution of the melts, and the intrusion to extrusion ratios typical of different environments.

The distribution of volcanic features on Venus (Fig. 1) is not concentrated along linear zones, such as the divergent and convergent plate boundaries concentrations seen on Earth. This, and the distribution of impact craters [3,4], is further evidence for the lack of large-scale crustal spreading in the last hundreds of millions of years. However, the distribution is not random, and there is evidence for a major Tharsis-like concentration in the Beta/Atla/Themis region that covers about 20% of the planet and is probably related to major mantle anomalies [1,13]. There is also a deficiency of many features in the lowlands and this is attributed to a combination of altitude-dependent eruption conditions [14] and partial burial of features in lowland regions. Ongoing detailed analysis of these

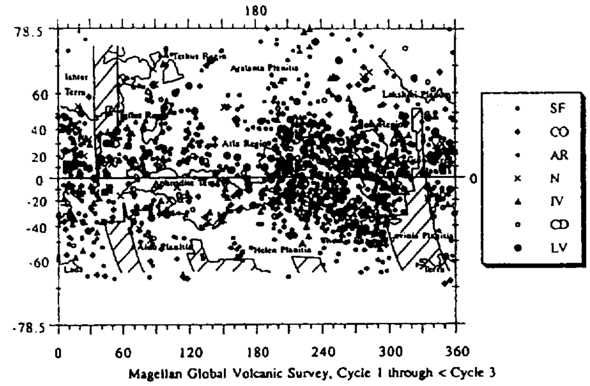

Fig. 1. Global distribution of volcanic features [1]. (SF = shield fields; CO = coronae; AR = arachnoids; N = novae; IV = intermediate volcanos CD = calderas; LV = large volcanos).

regions covered by repeat imaging is designed to detect volcanic deposits emplaced between cycles, but so far the duration of observations has been small and no changes that could be confidently attributed to volcanic activity have been observed.

On the basis of these analyses, what are the rates, styles, and nature of crustal formation processes on Venus [15]? The global distribution of volcanic features shows that volcanism is widespread across the planet and that in the time period represented by the present surface, volcanism was active at one time or another on virtually every part of the planet. Crustal formation processes clearly are linked to vertical differentiation and vertical crustal growth, in contrast to the lateral crustal spreading and lateral crustal propagation typical of the Earth's seafloor. Although the general factors involved in this process are known (e.g., extrusion, intrusion, and underplating), the details of the relative importance of each of these components and the mechanisms of resurfacing to produce the observed volcanic and impact crater record are not.

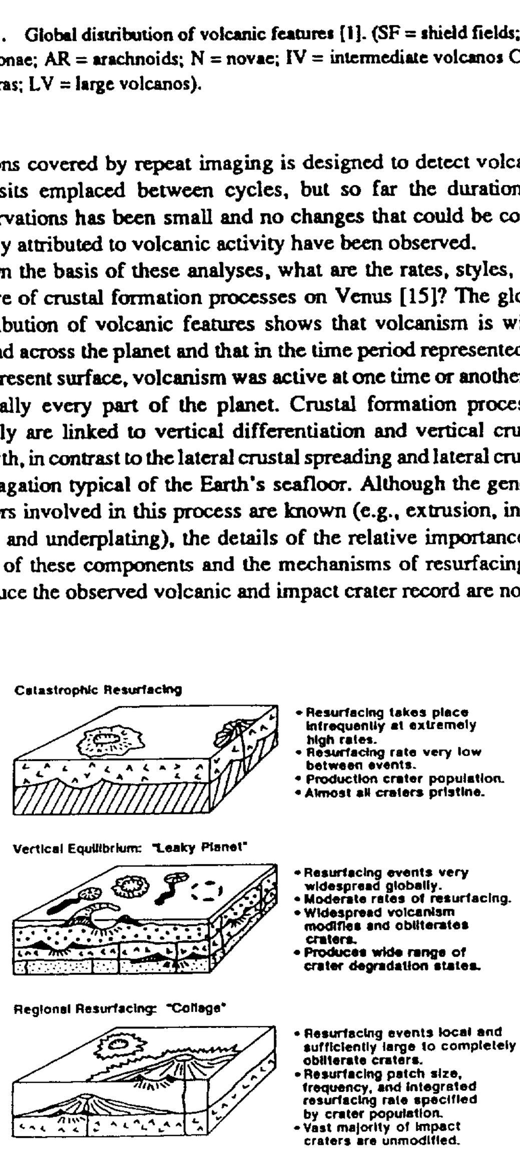

Fig. 2. Volcanic resurfacing models for Venus. Block diagrams illustrate the three types of crustal resurfacing scenarios consistent with the observed impact crater population.

The observed crater population on Venus can lead to three possible endmember resurfacing models [3], and the volcanic record [1] bears on the assessment of these (Fig. 2). The scale of volcanic features and deposits suggests that each feature covered areas much less than about 125,000 km^2, and that resurfacing may have proceeded by serial emplacement of local to regional features and deposits. Serial volcanism is visualized as a sequence of volcanic events varying in time and space, but ultimately influencing the whole planet over the timescale of hundreds of millions of years. In the serial volcanism or regional resurfacing process, volcanism proceeds in somewhat of a "collage" or "cookie-cutter" mode; volcanic features are produced in different parts of the planet at different times and because of the low crater density and small area covered by crater deposits, volcanic deposits can commonly be emplaced in a "matrix-filling" mode between craters; however, when they are emplaced on a crater, they tend to obliterate it (Fig. 2). Evidence in support of serial volcanism as a process is the large number of features that appear to be related to mantle instabilities on the scale of several hundred kilometers (shield fields, coronae, arachnoids, novae, large volcanos). These data suggest that the majority of near-surface melting is linked to pressure-release melting associated with mantle plumes or hot spots, rather than globally pervasive shallow melting as would be envisioned in the equilibrium resurfacing endmember model. However, the total volume of extrusive volcanism associated with these features is much less than that predicted by the model, but it is also clear that large areas of plains have been emplaced by mechanisms other than the features mapped here, and by processes not completely understood. The serial volcanism or regional resurfacing concept is in contrast to a "leaky planet" model, in which volcanism is much more uniformly distributed with time and is proceeding almost everywhere simultaneously (Fig. 2). In this case the crust is thickening relatively uniformly with time. The paucity of impact craters in intermediate to advanced stages of burial favors the serial volcanism or catastrophic resurfacing model over the "leaky planet" model; however, there is a level of uncertainty about the exact number of craters that actually postdate the surface, as described above. The "catastrophic resurfacing" model end member interprets the crater population to be a production population and calls on a pulse of resurfacing about 500 m.y. ago of sufficient thickness to obliterate the preexisting crater population and to produce a pristine surface on which the production population accumulates [4]. Volcanism subsequent to this time is viewed as minor and volumetrically minimal. The small number of impact craters highly modified by volcanism is viewed as supporting this hypothesis, and the total volume associated with the features observed [1] implies a low rate of volcanism, less than that implied by the serial volcanism model. However, a major unknown is the volume and mode of emplacement of the plains not related to the features mapped in this study. These plains may have formed as part of the catastrophic resurfacing event, or they may represent the sequential emplacement of deposits over the last several hundred million years. The stratigraphy, mode of emplacement, and scale of the plains-forming events is one of the major problems in Venus geology and volcanology at the present time, and detailed regional and global geologic mapping is required to begin to address this problem. Although the catastrophic resurfacing model seems unusual from a uniformitarian point of view, one must nevertheless remember that we may be dealing with differences in the thermal evolution of Venus relative to Earth, or in the consequences of long-term and continuous vertical crustal formation (Fig. 2), and the production of major instabilities in a depleted mantle layer [16]. Refinement of catastrophic resurfacing models 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

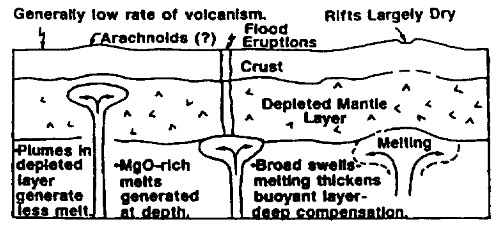

Fig. 1. Stationary thick depleted mantle layer.

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

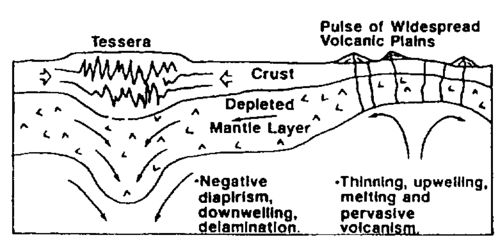

Fig. 2. Instabilities that develop in a depleted layer.