solar radiation, the actual solar flux required to create "moist" or "runaway" conditions would be higher than the values quoted above. (Indeed, some authors [12] have argued that cloud feedback would prevent a runaway greenhouse from ever occurring.) Early in solar system history, solar luminosity was about 25% to 30% less than today, putting the flux at Venus' orbit in the range of 1.34 S_0 to 1.43 S_0. Thus, it is possible that Venus had liquid water on its surface for several hundred million years following its formation. Paradoxically, this might have facilitated water loss by sequestering atmospheric CO_2 in carbonate rocks and by providing an effective medium for surface oxidation.

Continued progress in understanding the history of water on Venus requires information on the redox state of the atmosphere and surface. The loss of an ocean of water (or some fraction thereof) should have left substantial amounts of oxygen behind to react with the crust. This oxygen would presumably be detectable if we had core samples of crustal material. Barring this, its presence or absence might be inferred from accurate measurements of lower atmospheric composition. Another spacecraft mission to Venus could help to resolve this issue and, at the same time, shed light on the question of whether clouds will tend to counteract global warming on Earth.

References: [1] Donahue T. M. and Hodges R. R. Jr. (1992) *Icarus,* in press. [2] Lewis J. S. (1972) *Icarus, 16,* 241–252. [3] Wetherill G. W. (1980) *Annu. Rev. Astron. Astrophys., 18,* 77–113. [4] Prinn R. G. and Fegley B. Jr. (1989) In *Origin and Evolution of Planetary and Satellite Atmospheres* (S. K. Atreya et al., eds.), 78–136, Univ. of Arizona, Tucson. [5] Donahue T. M. et al. (1982) *Science, 216,* 630–633. [6] McElroy M. B. et al. (1982) *Science, 215,* 1614–1618. [7] Grinspoon D. H. and Lewis J. S. (1988) *Icarus, 74,* 21–35. [8] Kasting J. F. et al. (1984) *Icarus, 57,* 335–355. [9] Kasting J. F. (1988) *Icarus, 74,* 472–494. [10] Kasting J. F. and Pollack J. B. (1983) *Icarus, 53,* 479–508. [11] Kumar S. et al. (1983) *Icarus, 55,* 369–389. [12] Ramanathan V. and Collins W. (1991) *Nature, 351,* 27–32.

N93-14332

VENUS TECTONIC STYLES AND CRUSTAL DIFFERENTIATION.

W. M. Kaula and A. Lenardic, University of California, Los Angeles CA 90024, USA.

P- 2

Two of the most important constraints are known from Pioneer Venus data: the lack of a system of spreading rises, indicating distributed deformation rather than plate tectonics; and the high gravity:topography ratio, indicating the absence of an asthenosphere. In addition, the high depth:diameter ratios of craters on Venus [1] indicate that Venus probably has no more crust than Earth. The problems of the character of tectonics and crustal formation and recycling are closely coupled. Venus appears to lack a recycling mechanism as effective as subduction, but may also have a low rate of crustal differentiation because of a mantle convection pattern that is more "distributed," less "concentrated," than Earth's. Distributed convection, coupled with the nonlinear dependence of volcanism on heat flow, would lead to much less magmatism, despite only moderately less heat flow, compared to Earth. The plausible reason for this difference in convective style is the absence of water in the upper mantle of Venus [2].

The most objective measure of the nature of motion that we can hope to infer is the spherical harmonic spectrum of its surface, or near-surface, velocities. A compact expression of this spectrum is a spectral magnitude M and slope n

$$\sigma_1(v) = M\, l^{-n} \tag{1}$$

where $\sigma_1(v)$ is the rms magnitude of a normalized spherical harmonic coefficient of degree l. A concentrated flow, characterized by large segments moving together, has a steep slope, thence a high value of n, while a distributed flow, with small segments, has a small value of n. We cannot measure velocities directly on Venus. But in a planet dominated by a strong outer layer, in which the peak stresses are at a rather shallow depth, the magnitudes of gravitational potential V and poloidal velocity v_s are coupled [3]

$$M(\delta V)/M(v_s) = 12\pi G\eta/g \tag{2}$$

where η is the effective viscosity of the lithosphere, the ratio of stress to strain rate over long durations. The value inferred from the magnitudes M for Earth is 4×10^{21} Pa-s, probably most influenced by subduction zones. Support for this model is that the gravity and velocity spectra on Earth have the same slope n to two significant figures, 2.3 [3,4]. On Venus the spectral slope of gravity, $n(\delta V)$, is appreciably lower over degrees that can be determined reliably—about 1.4 [4], strongly suggesting a more regional, less global, velocity field than on Earth.

A basic constraint on the velocity field that is somewhat independent of stresses, and thence rheology, is that, at the mantle depth where convection dominates—more than 150 km—there must be a correlation of vertical velocity v_r (coupled to the poloidal velocity v_s by continuity) and temperature variations ΔT that lead to an integral accounting for most of the total heat delivery Q from greater depths

$$Q = \int \rho C v_r \Delta T\, dS \tag{3}$$

For a mean heat flow of 60 mW/m^2 and average temperature variation ΔT of 100°C, equation (3) gives an estimate of 0.6 cm/yr for v_r. In the Earth, plate tectonics lead to such concentrations of v_r and ΔT at shallower depths that it is difficult to draw inferences from observed heat flow relevant to equation (3). However, the constraint exists, and its implication for the velocity spectrum of Venus should be explored.

The altimetry and imagery of Venus also indicate a regionality of Venus tectonics, even though magnitudes of velocities cannot be inferred because of dependence on unknown viscosity. For example, Maxwell Montes is comparable to the Andes in height and steepness (suboceanic). But the material subducted under the Andes clearly comes from the southeast Pacific Rise, over 4000 km away (despite the interruption of the Nazca Rise), while only 500 km from the Maxwell front is a scarp, and beyond that a much more mixed, apparently unrelated, variety of features. Clearly, Maxwell is more local than the Andes. A significant difference of Venus tectonics from Earth is the absence of erosion, which removes more than 1 km/100 m.y. from uplands.

Hypotheses for why Venus does not have crustal formation in a ridge system, but rather a more distributed magmatism correlated with a more regional tectonism, include (1) the lack of plate pull-apart due to inadequate subduction; (2) the lack of plate pull-apart due to drag on the lithosphere from higher viscosity: i.e., no asthenosphere; (3) the lesser concentration of flow from within the mantle, also due to higher viscosity; (4) lower temperatures, due to less initial heating and more effective retention of lithophiles in the crust; (5) higher melting temperatures, due to lack of water content, and (6) lower mobility of magma relative to matrix, due to (a) low

H_2O content, (b) low-density overburden, or (c) lesser horizontal length scale of flow.

Relevant to these hypotheses is that differentiation on Venus requires more than adiabatic upwelling and pressure-release melting. In models of this process on Earth [e.g., 5,6] the availability of mantle material to flow into the region is taken as given; the concern is about the rising of magma within a solid matrix, in particular, the mechanism(s) concentrating the melt in a narrow vertical slab. The viscosity of the melt, and hence its ability to separate, is affected by water content. Differentiation from a plume, without pull-apart, under a layer of higher strength or lower density (as is more likely on Venus), requires a surplus of heat, and thus is likely to lead to a lower rate of magmatism for a given heat flow. Also the inhibition of upward flow by a low-density overlying layer may lead to less differentiation of crust. Application of models of a plume under a lithosphere [7] to Venus features such as Atla and Beta indicate that appreciably higher upper mantle viscosities may cause pressure gradients to account for these great peaks in the geoid.

We have applied finite element modeling to problems of the interaction of mantle convection and crust on Venus [8]. The main emphasis has been on the tectonic evolution of Ishtar Terra, as the consequence of convergent mantle flow. The early stage evolution is primarily mechanical, with crust being piled up on the downstream side. Then the downflow migrates away from the center. In the later stages, after more than 100 m.y., thermal effects develop due to the insulating influence of the thickened crust. An important feature of this modeling is the entrainment of some crustal material in downflows.

An important general theme in both convergent and divergent flows is that of mixing vs. stratification. Models of multicomponent solid-state flow obtain that lower-density crustal material can be entrained and recycled, provided that the ratio of low-density to high-density material is small enough (as in subducted slabs on Earth). The same considerations should apply in upflows; a small percent partial melt may be carried along with its matrix and never escape to the surface. Models that assume melt automatically rising to the crust and no entrainment or other mechanism of recycling lower-density material [e.g., 9] obtain oscillatory behavior, because it takes a long time for heat to build up enough to overcome a Mg-rich low-density residuum. However, these models develop much thicker crust than consistent with estimates from crater depth:diameter ratios [1].

References: [1] Sharpton V. L. and Edmunds M.S. (1991) *Eos, 72*, 289. [2] Kaula W. M. (1992a) *Proc. IUGG Symp. Chem. Evol. Planets*, in press. [3] Kaula W. M. (1980) *JGR, 85*, 7031. [4] Kaula W. M. (1992b) *Proc. IAG Symp. Grav. Field Det. Space Air Meas.*, in press. [5] McKenzie D. P. (1985) *EPSL, 74*, 81. [6] Scott D. R. and Stevenson D. J. (1989) *JGR, 94*, 2973. [7] Sleep N. H. (1990) *JGR, 95*, 6715. [8] Lenardic A. et al. (1991) *GRL, 18*, 2209. [9] Parmentier E. M. and Hess P. C. (1992) *LPSC XXIII*, 1037.

N93-14333

LARGE SHELD VOLCANOS ON VENUS: THE EFFECT OF NEUTRAL BUOYANCY ZONE DEVELOPMENT ON EVOLUTION AND ALTITUDE DISTRIBUTION.

S. Keddie and J. Head, Department of Geological Sciences, Brown University, Providence RI 02912, USA.

The Magellan mission to Venus has emphasized the importance of volcanism in shaping the surface of the planet. Volcanic plains make up 80% of the terrain and hundreds of regions of localized eruptions have been identified. Large volcanos, defined as edifices with diameters greater than 100 km, are the sites of some of the most voluminous eruptions. Head et al. [1] have identified 158 of these structures. Their spatial distribution is neither random (see Fig. 1) nor arranged in linear chains as on the Earth; large volcanos on Venus are concentrated in two large, near-equatorial clusters that are also the site of many other forms of volcanic activity [1].

The set of conditions that must be met on Venus that controls the change from widespread, distributed volcanism to focused, shield-building volcanism is not well understood. Future studies of transitional features will help to address this problem. It is likely, however, that the formation and evolution of a neutral buoyancy zone (NBZ) plays an important role in both determining the style of the volcanism and the development of the volcanic feature once it has begun to erupt. Head and Wilson [2] have suggested that the high surface pressure on Venus may inhibit volatile exsolution, which may influence the density distribution of the upper crust and hence control the nature and location of a NBZ. The extreme variations in pressure with elevation may result in significantly different characteristics of such a NBZ at different locations on the planet. In order to test these ideas regarding the importance of NBZ development in the evolution of a large shield and to determine the style of volcanism, three large volcanos that occur at different basal elevations were examined and the distribution of large volcanos as a function of altitude was determined.

The evolution of Sapas Mons, a 600-km-diameter shield volcano, was studied [3]. Six flow units were identified on the basis of radar properties and spatial and temporal relations. The distinctive variation between units was attributed to the evolution of magma in a large chamber at depth. The presence of summit collapse structures and radial fractures, interpreted to be the surface expression of lateral dikes, supports this suggestion. Theory predicts that volcanos located at the altitude of Sapas Mons should have large magma chambers located at zones of neutral buoyancy at relatively shallow depths beneath the substrate [2]. Not only does the evidence from the flow units suggest that such a zone is present, but the size of the summit collapse and the near-surface nature of the radial dikes indicates that the chamber is both large (on the order of 100 km in diameter) and shallow.

In comparison to Sapas Mons, two other volcanos at different elevations were examined. Theory predicts that the volcano at the

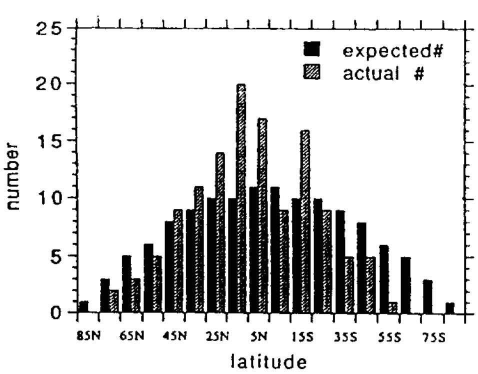

Fig. 1. Location of large volcanos as a function of latitude. The dark-shaded columns indicate where volcanos would be located if they were randomly distributed on the surface as a function of the percentage of area at a given latitude. The striped columns show where the volcanos actually occur. Note the paucity of volcanos at higher latitudes and the concentration in the equatorial region of the planet.