MAGMA RESERVOIRS AND NEUTRAL BUOYANCY ZONES ON VENUS:

We have developed models for the production of magma reservoirs and neutral buoyancy zones on Venus and have assessed the implications of their development for the formation and evolution of volcanic landforms (1). Major factors in the ascent and emplacement of magma include: 1) phase of ascending material: mantle materials in buoyant ascent undergo pressure-release partial melting to produce primary reservoirs - subsequent migration and stalling of partial melts at rheological or density traps produce secondary reservoirs; 2) rheological boundaries: important in determining the depth and geometry of buoyant rising mantle materials and their associated primary reservoirs and in determining the mode of emplacement of magma bodies in secondary reservoirs; 3) density boundaries: important in forming neutral buoyancy traps and secondary reservoirs for ascending magma due to compositional differences, phase differences, and density differences related to degassing and weathering. The actual configuration and evolution of magma bodies is a function of various combinations of these three factors.

Two major styles of magma ascent are likely to occur on Venus and to produce a bimodal distribution of reservoirs: 1) those associated with regions of plastic deformation: mantle upwelling, plume and diapir formation, and pressure-release melting in the upper mantle to produce deep magma reservoirs (2): the generally stationary position of the lithosphere of Venus relative to the interior means that primary reservoirs will grow to very large sizes; 2) those associated with the outer, more nearly elastic regions, where brittle fracture and dike propagation are the primary mechanisms of magma transport: neutral buoyancy zones (NBZ's) in this outer region can cause stalling of magma rising in dikes and can result in the production of shallow magma reservoirs in the depth range of one to several kilometers (3).

The high atmospheric pressure on Venus reduces volatile exsolution (4) and generally serves to inhibit the formation of NBZ's and shallow magma reservoirs. A major difference between rock column density profiles on Earth and Venus is that on Earth a very wide range of volatile contents leads to explosive disruption of magma (fire fountaining) and associated gas loss, after which the bulk density is about 2200 kg/m³, while on Venus explosive disruption is rare, and the extruded lavas retain whatever amount of gas they can exsolve. They thus can actually achieve densities that are lower than those of magmas with initially comparable volatile contents on Earth. For a range of common terrestrial magma volatile contents, magma ascending and erupting near or below mean planetary radius (MPR) on Venus should not stall at shallow magma reservoirs; such eruptions would be characterized by relatively high total volumes and effusion rates and intrusion to extrusion ratios would be low. For the same range of volatile contents at 2 km above MPR, about half of the cases result in direct ascent of magma to the surface and half in the production of neutral buoyancy zones. In general, neutral buoyancy zones and shallow magma reservoirs begin to appear as gas content increases and, because of the high atmospheric pressure, are nominally shallower on Venus than on Earth. For a fixed volatile content, NBZs become deeper with increasing elevation: over the range of elevations treated here (-1 km to +4.4 km) depths differ by a factor of 2-4, which is about the same factor as that induced by variations in CO₂. NBZ reservoirs can become deeper than reservoirs on Earth produced with similar volatile contents if common terrestrial volatile content limits are exceeded.

These analyses reveal several factors that may help to account for the low height of volcanoes on Venus. Larger primary reservoirs cause the wide dispersal of conduits building edifices. Models of the position of the shallow NBZ reservoir during edifice growth show that, for Earth, the magma chamber center remains at a constant depth below the growing edifice summit, thus keeping pace with the increasing elevation, while on Venus the chamber
center becomes deeper relative to the summit of the growing edifice because of the major change in atmospheric pressure as a function of altitude. Therefore, neutral buoyancy zones and magma reservoirs on Venus will remain in the pre-volcano substrate longer and in many cases may not emerge into the edifice at all, and the lower rate of vertical migration implies that magma reservoirs would tend to stabilize, undergo greater lateral growth, and become larger on Venus than Earth. In these cases the intrusion to extrusion ratio should be relatively high. The proportion of the available magma going into production of the edifice relative to that intruded into the substrate is smaller on Venus than Earth. Large reservoirs would encourage multiple and more widely dispersed source vents, large volumes for individual eruptions, and would encourage a range of differentiation processes (volatile exsolution, fractional crystallization, and remelting of country rock). All of these factors favor the production of broad, low edifices comparable to those observed on Venus. Subsidence due to loading, a factor known to reduce the elevation of volcanoes both during and subsequent to their growth on Earth, could be enhanced on Venus due to the thermal effects of a relatively larger magma reservoir.

In large reservoirs, positively buoyant materials are likely to be produced from differentiation, substrate remelting, and volatile exsolution. Non-buoyant materials exsolving volatiles in a shallow reservoir will need higher gas bubble concentrations to produce eruptions than on Earth, and when this gas-enriched melt emerges at the surface, it is more likely to retain its bubbles than to undergo explosive disruption due to the high surface atmospheric pressure. Therefore there is the potential for the production of a range of erupted lavas that have very high gas bubble concentrations, leading to anomalous, more viscous rheological properties. Inhibition of disruption of volatile-rich magma for both basaltic and more evolved compositions can lead to the production of: 1) more bubble-rich, vesicular flows characterized by higher viscosity and greater thicknesses, the Venus equivalent of effusions that would have lost much of their volatiles in the fire-fountaining process on Earth, 2) high volume, high discharge rate extremely gas-rich basaltic effusions that increase viscosity considerably upon surface extrusion, and produce domes whose volumes are considerably higher than their dense-rock equivalent, and 3) more evolved compositions that are gas-rich but do not undergo disruption upon effusion, and produce domes and flows of high viscosity, the Venus equivalent of terrestrial ignimbrites.

These theoretical treatments provide a basis for predictions concerning volcanic landforms on Venus. Intrusions and dike emplacement should be common, particularly around both shallow and deep magma reservoirs, and the tops of dikes should be manifested as radial fractures and troughs. There should be a range of diameters of circular features associated with the presence of both shallow (NBZ-related) and deep (plume-related) magma reservoirs. Large-volume lava outpourings should be favored at lower elevations, and shallow reservoirs and edifices more common at intermediate elevations; at highest elevations, magma reservoirs are predicted to be large and relatively deep with low associated edifices. Direct ascent of magma where neutral buoyancy zones are less likely (low elevations) and the propensity for relatively larger magma reservoirs on Venus when they do form, are both factors which will tend to favor high-volume eruptions, independent of variations in magma temperature or chemistry. Intrusion to extrusion ratios (I/E) are likely to be quite variable on Venus (presence of larger plume-related reservoirs and NBZ reservoirs on Venus than on Earth mean high I/E; inhibition of NBZ development at low elevations means low I/E). Individual volcanic features should be interpreted in terms of regional geologic setting and the dynamics of elevation changes commonly associated with various scales of mantle processes and magma emplacement in order to assess global crustal growth processes on Venus.