
INTRODUCTION. The Venus cratering record has been interpreted in terms of a geologically recent (~300-500 Ma ago), possibly catastrophic global tectonic and volcanic resurfacing event followed by diminished levels of activity [1]; we examine the stratigraphic and volcanic record [2] and its petrogenetic implications [3] in order to test this model and understand its consequences (Fig. 1). We find that there are definite planet-wide changes in volcanic and tectonic style and flux with time and that volcanic changes can be interpreted in terms of variations in the depth and percent partial melting. Although peak flux decreased with time, the average flux was apparently never much more than values typical of recent global volcanism on Earth. These observations suggest that early tessera-related tectonism was the major factor in the eradication of pre-existing impact craters and that post-tessera volcanism was areally widespread but volumetrically relatively low.

STRATIGRAPHY, MORPHOLOGY, COMPOSITION, THICKNESSES, AREAS, VOLUMES AND FLUXES. Early Magellan results [4] and recent stratigraphic analysis [2] show that volcanic plains are areally very significant on Venus (>80% of the surface) and are stratigraphically younger than the relatively intensely deformed tessera terrain (~8% of the surface) [5]. Although pervasive deformation of tessera terrain obscures the nature of previous rock units, volcanic plains have been detected beneath tessera overprints in Tellus and Ovda [6]. The oldest units embaying the tesserae are extensive deposits of densely fractured plains (Pdf) of volcanic origin. In part, the deformation associated with these plains is coincident with the Phase II extensional deformation of the tesserae; evidence of volcanic style is obscured by deformation in this (Pdf) and related units (Pfr, fractured and ridged plains). Superposed on this unit are relatively undeformed plains characterized by abundant small volcanic shields (Psh) [7]. These features are evidence for widespread shallow volcanic sources and relatively low effusion rates at these sources [8]. Following this, widespread radar-dark volcanic plains (Pwr) are emplaced globally (>70% of the surface). These plains show little evidence for abundant distributed volcanic sources typical of Psh; instead, source regions are not obvious, and the major features are long sinuous channels many of which are similar to lunar sinuous rilles formed from high effusion rate, long duration eruptions [9]. Stratigraphic evidence suggests that these plains were initially emplaced in widespread flood events, and partially through canali. Canali are interpreted to represent picritic or komatiitic lavas formed by large degrees of partial melting [3], but they could also be emplaced by more exotic magmas [10]. Emplacement of these plains was followed by compressional deformation in the form of wrinkle ridges. Following this, another change in style and mode of occurrence of volcanism is observed. Widespread plains units were largely followed by the formation of broadly distributed central volcanic edifices and sources [11], and decreasing global fluxes [12]. Latest activity is localized at edifices on broad volcanic rises [13], and at rifts where lithospheric thinning has permitted locally enhanced melting and volcanism [14]. Using the percentage areas covered by each unit [2] and estimates of the thickness based on superposition relationships and local and global flooding models [5, 15] we have calculated the total volumes for the post-tessera volcanic plains and the volume of each unit. For example, if post-tessera pre-Pf regional plains of volcanic origin (Pfr -> Pwr) cover ~85% of the planet and average thicknesses are less than ~2 km, then fluxes are on the order of 4-8 km3 a-1 for 100-200 Ma emplacement durations (Fig. 2). Late large scale effusion (average area 220 x 103 km2) cover about 11% of the Venus plains and ~74% are located in zones of extension (major rifts and fracture belts) [15]; if these were emplaced over a period of at least 100 Ma, then fluxes would be less than 0.25 km3 a-1. These trends show a definite decrease in average flux but uncertainties in the age of the individual surface units and the duration of their emplacement [17] mean that there is a wide range of uncertainties in the flux estimates. Nevertheless, peak average fluxes are still considerably below the typical recent terrestrial total crustal production rates (~30 km3 a-1) and much more in the range of values typical of recent terrestrial total global volcanism rates (for the early stage on Venus) and intraplate volcanism (for the later stage) (Fig. 2). It must be kept in mind that average fluxes can be readily exceeded by peak fluxes associated with individual emplacement events or units; on the Moon single emplacement events may have exceeded the peak mean flux by a factor of 70,000 [18] and on Earth emplacement of individual large igneous provinces [19] may have equaled or exceeded the flux from all other sources.

SUMMARY AND INTERPRETATIONS. On the basis of these observations, we conclude that the most consistent scenario is one in which tessera formation was accompanied and followed by areally vast outpourings of lava; earliest deposits were deformed by extension and some shear (Pdf), and later are deformed by regional and local-scale compression (Pfr, RB, Pwr) decreasing in intensity with time. Volcanic styles suggest early post-tessera widely distributed shallow sources followed by very voluminous sources with high degrees of partial melting and a deeper range of melting depths; average fluxes may have exceeded 5 km3 a-1 in this period but the
global integrated flux is still relatively low. Subsequent volcanism is more limited, centralized, and localized, and styles suggest deeper sources and thicker lithosphere; rates were << km3 a-1, comparable to present terrestrial intraplate volcanism. Recent average fluxes on Venus still far exceed the average lunar mare flux (10-2 km3 a-1) during the peak period of mare emplacement [18].

Models of monotonic thermal decay [20] do not easily account for the major decline in flux or the change in volcanic style. Plate tectonic models [21] also do not easily explain these observations. A depleted mantle layer overturn model [22] is consistent with many of the observations. In this scenario, a depleted mantle layer underlying a vertically accreting crust becomes unstable and overturns, causing localized crustal thickening (tessera) and extensive volcanism linked to crustal thinning (Psh) and pressure-release melting of upwelling fertile mantle at a range of depths (Pwr). Such mantle upwelling would favor komatiitic magmas produced at deeper levels and high effusion rate fluid lavas at the surface. In this scenario this near-surface thermal and magmatic pulse is followed geologically rapidly by stabilization, cooling and lithospheric thickening, widespread compression, and localization of volcanism to sources related to deeper mantle convection and lithospheric thinning. These data on flux and style provide a basis on which to further test and refine or reject these and other models.


Figure 1. Rates of terrestrial magmatism, plutonism, and volcanism compared to Venus [after 4 using data from 23]. Figure 2. Diagrammatic representation of Venus stratigraphy and tectonic/volcanic processes.

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