PROTOCONTINENT ACCRETION FROM PLUME PLATEAUS ON VENUS AND ON EARLY EARTH;

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INTRODUCTION. The process and timing of continent formation on Earth are unknown, but continents are believed to represent areas of anomalously thickened crust that nucleated in the early Archean, grew relatively rapidly, and continued to accrete with other areas of thickened crust over geologic time. Many of the thermal and rheological characteristics of current Venus are analogous to early Earth and afford opportunities to further evaluate the nature of early crustal formation under such conditions. Recent studies of Venus imply that a variety of mechanisms of crustal production occur and suggests that highland areas represent areas of continent-like anomalously thick crust [1]. Elsewhere we have shown the possible significance of mantle plumes [2,3,4] in the production of such plateaus ("plume plateaus"). In the following we describe a model for the formation of protocontinental areas on Venus from plume plateaus and their relation to continent-like highland areas on Venus. We then investigate the possibility that a similar process may have operated on early Earth during the initial formation of continents.

PLATEAUS on VENUS. Plateau-like areas elevated from one to three kilometers above mean surface elevations and hundreds to thousands of kilometers across are widely distributed over the surface of Venus and account for approximately 20% of the surface area. We define plateaus as areas with surface elevations enhanced by 1.5 to 3 km relative to the mean global surface, enhanced relief (1.5 to 2 km) relative to the local surface, low mean large-scale upper surface relief, surfaces generally within ±2 km in altitude over several hundred kilometers, and bordered on at least three sides by regionally steep (≥0.5°) slopes.

Areas with these topographic characteristics in the equatorial latitudes form the great circle belt of equatorial highlands and are the sites of rifting, volcanism [5], tectonic junctions [6], large scale trends in surface slopes [7]. Dynamic mantle upwelling [8, 9], crustal spreading [10,11,12] at rates of a few centimeters per year, and a combination of the two processes [2] are interpreted to be occurring in Aphrodite Terra.

In contrast, plateaus in the high latitudes cluster together and are not obviously associated with rifting at present. Instead the geologic characteristics of crustal shortening dominate [13] where areas of differing internal tectonic patterns and structural orientations appear to juxtaposed, are characterized by evidence for geological structures associated with convergent processes including locally intense crustal shortening, associated overthrusting and further crustal thickening, by orogenic belts [14,15] and apparent collage-like suturing together of several crustal blocks [13] in convergent settings

Plateaus in the mid latitudes are variable and characterized by margins bounded by ridge belts indicative of moderate marginal deformation, structurally complex tessera-like surfaces and both shallow (Tellus) [16] and deep (Bell Regio) [17] compenstion suggesting local support of the elevated plateaus by either greater crustal thickeness or mantle upwelling and associated volcanism. The occuirrence of large elevated volcanic regions such as Bell Regio suggest that there plume plateau production may occur from volcanic crustal thickening and away from rifting and divergent settings.

ORIGIN and EVOLUTION of PLATEAUS on VENUS. The current distribution, occurrence in diverse tectonic settings, and range of plateau formation and modfication mechanisms in these settings suggests a distinctive evolutionary sequence for each plume plateau [2,3]. Plume plateaus formed in divergent settings will be split and separated into conjugate plateaus following the decay and collapse of the responsible mantle plume [18]. The subsequent history of plume plateaus formed in both divergent and non-divergent settings will be similar: the plateaus will move away from the diveregent boundary and stagnate in areas of mantle downwelling [19] where the thicker than average crust of the plateaus will be stable against destruction compared to nominal-thicknesss crusts, and it will resist underthrusting, coalesce to form larger plateaus, and become the locus for further accretion by intercepting other plume plateaus as they arrive at the site of mantle downwelling. This model suggests that the large collage of plateaus in the high latitudes of Venus (Ishtar Terra) may have aggregated over geologic time from the collage accretion process and might represent an analog to protocontinents.

IMPLICATIONS for EARTH. It has been suggested that the precursors to modern continents were accreted in the Archean from large collages of mafic oceanic plateaus [20], many of which may have formed in settings similar to those in low to mid latitudes of Venus (divergent and plume environments). We suggest that the formation, dispersal, and subsequent collage accretion of large plume plateaus during the Archean on Earth like those on Venus might explain evidence for the rapid formation and evolution of protocontinents and the widespread occurrence of mafic, oceanic-plateau-like terranes in Archean cratons. Venus might be an actual model for the formation of protocontinents on Archean Earth.

Oceanic Plateaus and Mantle Plumes. Oceanic plateaus are areas of anomalously thick crust [21] of oceanic (mafic) composition, although some are possibly slivers of continental crust [22], and some represent uplift associated with mantle upwelling. One characteristic that oceanic plateaus share in common is the geochemical and isotopic characteristics of mantle melts generated at intraplate mantle plumes; many also have the depleted geochemical characteristics typical of normal mid-ocean ridge basalts. Iceland is an example of an oceanic plateau interpreted to be actively forming where a hot spot or mantle plume is superposed on the Mid-Atlantic ridge [23], illustrates how these mixed geochemical characteristics could originate and is an example of a plume plateau associated with the process of crustal spreading on Earth. Linear plume-track volcanic island chains, such as the Hawaii-Emperor chain, are plateau-like areas of anomalously thick oceanic crust, formed far from areas of crustal spreading, and illustrate that the presence of crustal spreading is not a requirement for plume plateau production. Together, these examples illustrate some of the ways in which plateaus may be associated with thicker than average crust at sites of mantle plumes.

Plume Plateaus and Continetal Growth. The presence of active plume plateaus today, together with the abundance of oceanic plateaus with plume plateau characteristics residing throughout the seafloor suggest that plume plateaus have formed throughout the Mesozoic and Cenozoic. The docking of many such plateaus together with marginal island arcs upon the western margin of the North American continent is believed to have contributed to the the growth of the western margin of the North America in this manner. Ophiolites in Paleozoic orogenic belts increasingly imply the occurrence of accreted mafic terranes analogous to oceanic plateaus throughout the Phanerozoic, and accretion of allochthounous terranes in general is believed to have contributed a significant fraction to the current Proterozoic and Phanerozoic volume of continental crust [24].

Plume Plateaus and Accretion of Protocontinents. Proterozoic and Archean terranes similar to modern oceanic plateaus [25] occur in mafic greenstone belts and cover extensive areas of the Precambrian interior of continental shields [26]. If the early protocontinents were accreted from plume plateaus as these suggest, the rates and scales of plume plateaus production early in Earth history must have been much greater than present rates in order to accumulate the observed early large volumes of Archean and early Proterozoic protocontinents.

The known thermal, petrologic, and rheological characteristics of the Archean crust and mantle on Earth are similar to many of the current observed and predicted characteristics of Venus. On the basis of inferred greater mantle temperature and increased degrees of partial melting, increased rates of crustal growth from plume plateau formation and subsequent accretion are predicted in the Archean relative to the present, particularly if the bulk chemistry of the upper mantle were less depleted, and the fequency of plumes and abundance of hot spots was greater relative to the present reflecting more vigorous early [27] global patterns of mantle upwelling. These characteristics suggest increased plume plateau production for early Earth history. Correspondingly large and abundant plume plateaus may have accreted into extensive collages to form early protocontinents.

CONCLUSIONS. We suggest that protocontinents on Earth arose from the accretion of many plume plateaus into large collages and in a manner similar to that interpreted to be responsible for the current aggregation and deformation of continent-like high latitude plateaus on Venus. The large mafic plateaus necessary for the early assembly of protocontinents on Earth might have originated from early large-scale plume plateaus associated with vigorous, deep, and frequent areas of mantle upwelling in the warmer early mantle.

This model raises fundamental questions about Venus: If current Venus is analogous to the conditions existing during the early rapid phase of continental growth on Earth, why has Venus generated a much smaller amount of thick plateau-like crust? Has the process of continental formation started later on Venus? Has the total rate of stable crustal production been slower, the rate of crustal loss greater, or crustal motion slower on Venus than Earth? Or does it reflect a fundamental difference such as larger plume-related heat transfer and smaller plate-related heat transfer, or changes in buoyancy of crust with time such that plateaus are stable against subduction only after relatively greater periods of time [28]?

REFERENCES. [1] Head, 1990, *JGR*, **95**, 7119. [2] Head and Crumpler, 1990, *Nature*, **346**, 525. [3] Crumpler and Head, 1990, *Lunar Planet Sci.* **21**, 254. [4] Herrick and Phillips, 1990, *GRL*, **17**, 2129. [5] Schaber, 1982, *GRL*, **9**, 499. [6] Senske, 1989, M.S.Thesis, Brown Univ. [7] Sharpton and Head, 1986, *JGR*, **91**, 7545. [8] Sjogren, et al., 1983, *JGR*, **88**, 1119. [9] Herrick and Phillips, 1990 *GRL*, **17**, 2129. [10] Head and Crumpler, 1987, *Science*, **238**, 1380. [11] Sotin et al, 1989, *EarthPlanetSciLet*, **95**, 321. [12] Crumpler, 1990, *Earth Moon Planets*, spec. Venus vol., in press. [13] Vorder Bruegge and Head, 1989, *GRL*, **16**, 699. [14] Crumpler et al, 1986, *Geology*, **14**, 1031. [15] Head, 1990, *Geology*, **18**, 99. [16] Bindschadler et al.,1990,*GRL*, **17**, 171. [17] Smerkar and Phillips, 1989, *Lunar Planet. Sci.*, **21**, 1176. [18] Crumpler and Head, 1990, *EOS*, **17**, 546 [19] Gurnis, 1988, *Nature*, **332**, 695. [20] Kroenke, 1974, *EOS*, **55**, 443. [21] Sandwell and MacKenzie, 1989, *JGR*, **94**, 7403. [22] Ben-Avraham et al., 1981, *Science*, **213**, 47. [23] Schilling et al., 1983 in *Struct. Devlopment of Greenland-Scotland Ridge*, Bott et al., eds., Plenum, 319. [24] Reymers and Schubert, 1984, *Tectonics*, **3**, 63.[25] Abouchami et al., 1990, *JGR*, in press. [26] deWit and Ashwal, 1987, *Workshop Tec. Evol. Greenstone Belts*, deWit and Ashwal, eds., LPI Tech Report **86-10**, 13. [27] Bercovici et al, 1989, *GRL*, **16**, 617. [28] Herrick and Parmentier, 1990, *Repts. Planet. Geol. Prg.-1989*, Holt,ed., NASA Tech. Mem. **4210**, 14.