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Venus's evolution: A synthesis

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ABSTRACT

Perhaps the most surprising result of the NASA (National Aeronautics and Space Administration) Magellan mission to Venus was the preservation of ~970 essentially pristine impact craters distributed in near-random fashion across the planet surface. The craters have been widely interpreted as evidence of near-global catastrophic volcanic resurfacing over 10–100 million years, ~500 million years ago. This view of Venus permeates textbooks and popular science, and is rarely questioned. The view of a catastrophically resurfaced Venus emerged relatively early in Magellan mission data analysis. We revisit the question of impact crater distribution and implications for Venus's resurfacing and evolutionary processes using the wealth of observations that have emerged from ~15 years of Magellan data analysis. The widely cited near-global catastrophic volcanic resurfacing hypothesis, although initially compelling, does not stand up to the rigors of detailed geologic mapping and analysis. A separate but related hypothesis, the global stratigraphy hypothesis, deems that catastrophic resurfacing involved the emplacement of 1–3 km thick stacks of lava flows, which buried preflood craters across ~80% of Venus's surface. However, geologic mapping indicates that thin, rather than thick, flows cover hypothesized preflood surfaces. In addition, the ~8% of the surface hypothesized as ancient preflood remnants in the global stratigraphy hypothesis, preserved in elevated plateaus, does not correlate spatially with Venus's oldest surfaces as indicated by impact crater density and crater morphology. Finally, extensive lowland regions, representative of the hypothesized flooded surface, correlate with some of the oldest surfaces on the planet, contrary to hypothesis predictions.

An alternative resurfacing hypothesis (the SPITTER hypothesis: Spatially Isolated Time-Transgressive Equilibrium Resurfacing), which combines aspects of previous hypotheses, calls for near-steady-state impact crater formation and destruction during a time of a globally thin lithosphere. Crater destruction occurred through time-integrated formation of numerous crustal plateaus, occurring in large local regions but punctuated in time and space. The SPITTER hypothesis does not depend on a particular mechanism of crustal plateau formation (whether by downwelling,

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plume, or impact-induced lava pond), but rather focuses on the elements common to all crustal plateau hypotheses. With a secular change to thick lithosphere, crater destruction processes could no longer operate, and the surface began to accumulate craters. Locally, young surfaces developed as a result of pronounced local volcano-tectonic activity in the Beta-Atla-Themis and Lada regions. We call for a thorough reanalysis of Venus resurfacing hypotheses with vigilant consideration of stated and unstated assumptions. The view that is emerging from geologic mapping of the spectacular Magellan data seems to provide tantalizing evidence that Venus's surface records a rich and long history, rather than an abbreviated view of the last ~500 million years as has been widely assumed.

Keywords: resurfacing, crustal plateaus, SPITTER, impact craters.

INTRODUCTION

How do terrestrial planets evolve? Do they follow generalized evolutionary patterns, or is each terrestrial planet unique? The NASA Magellan mission set out to understand the evolution and planetary dynamics of what was believed at the time to be the most Earth-like planet in our solar system—Venus. Understanding Venus's evolution is particularly significant given Earth-Venus similarities in age, mass, radius, solar distance, and presumed similarity in bulk composition, rates of heat generation, and energy available to drive internal convection—all characteristics that should impose first-order effects on terrestrial planet dynamics and evolution. From 1990 to 1994 the NASA Magellan satellite returned high-resolution gravity, altimetry, emissivity, and synthetic aperture radar (SAR) data sets (Saunders, 1992; Ford et al., 1993); these data, together with early data from Soviet Venera missions, Pioneer Venus, and the Arecibo observatory, provide incredible views of Venus's surface.

Perhaps the most surprising result to emerge from the Magellan mission was the occurrence of ~970 pristine impact craters preserved in apparent random distribution across Venus's surface (Phillips et al., 1992; Schaber et al., 1992; Herrick et al., 1997). Because impact crater density reflects the relative age of planet surfaces (older surfaces display higher crater density), the near-random spatial distribution of craters indicates that Venus lacks large regions of very young and very old surfaces. In global Magellan altimetry data, Venus shows a dominance of circular features at a wide range of scales, and lacks long linear topographic highs and lows. On Earth, large tracts of young and old crust, and long linear topographic highs and lows, represent characteristic signatures of terrestrial plate-tectonic processes. Thus Magellan data provided clear evidence that Venus lacks plate-tectonic processes (Solomon et al., 1991, 1992; Solomon, 1993; Phillips and Hansen, 1994). This result fueled much excitement; Venus, Earth's sister planet, must transfer interior heat to the surface through different dynamic processes than Earth, and it must have followed a different evolutionary path than Earth. Yet, almost 15 years since the return of the first spectacular views of Venus's surface, the nature of Venus's evolution, and many of the operative dynamic processes, remain elusive.

How did Venus acquire the near-random impact crater spatial distribution, and what are the implications for Venus's evolution? A plethora of hypotheses emerged to address these questions. After limited debate, much of the planetary community seems to have settled on a dominant hypothesis: Circa 500 Ma, Venus experienced catastrophic resurfacing involving an outpouring of massive volumes of flood lava, covering ~80% of the surface in 10–100 m.y. (e.g., Schaber et al., 1992; Strom et al., 1994, 1995; Herrick, 1994; Basilevsky and Head, 1994, 1996, 1998, 2002; Ivanov and Head, 1996; Head and Coffin, 1997; Basilevsky et al., 1997; Head and Basilevsky, 1998; Grinspoon, 1998; Nimmo and McKenzie, 1998; Anderson and Smrekar, 1999; Solomon et al., 1999; Turcotte et al., 1999; Bullock and Grinspoon, 2001). This interpretation led to investigations aimed at understanding the cause and effect of the hypothesized flooding. In short order, the catastrophic volcanic resurfacing hypothesis seemed to rise above the level of debate, where today it is considered an (almost) undisputed fact of Venus's evolution. It permeates general textbooks and popular science accounts, and it forms an essentially implicit (often required) assumption for scientific contributions. Despite the widespread acceptance, catastrophic volcanic resurfacing represents but one of many possible interpretations of a single statistical data set (and a handful of impact crater characteristics that served as model constraints). A growing body of data is inconsistent with the predictions of that hypothesis.

Given the enormity of the implications of the entrenched catastrophic volcanic resurfacing hypothesis, which emerged from initial mission reports, it seems prudent to revisit the resurfacing debate with the advantage of postmission data analysis. Geologic mapping reveals a growing number of relationships that pose serious challenges to the catastrophic volcanic resurfacing hypothesis, as discussed herein. The catastrophic volcanic resurfacing hypothesis deems that thick stacks of lava flows bury preflood craters across ~80% of Venus's surface; however, craters marked by significant levels of burial have not been identified. In contrast, postmission geologic mapping indicates that thin, rather than thick, lava covers the hypothesized preflood surfaces. In addition, the ~8% of the surface hypothesized as representative of preflood surface remnants (and thus "ancient"), preserved in elevated plateaus, does not correlate spatially with Venus's oldest surfaces as indicated by impact crater density and morphology. Finally, extensive lowland regions, representative of the hypothesized flooded surface, correlate with some of the oldest surfaces on the planet, contrary to hypothesis predictions. In this contribution, we review aspects of the resurfacing debate, outline observations that must be accommodated within any resurfacing hypothesis, discuss challenges the observations pose for existing resurfacing hypotheses, and present an alternative resurfacing hypothesis that appears to address all current constraints. This contribution calls for critical reanalysis of Venus's resurfacing free of the a priori assumption of catastrophic resurfacing.

BACKGROUND

Venus and Earth share many similarities, yet they also have profound differences. Venus, 0.72 AU (Astronomical Unit) from the Sun, is 95% and 81.5% Earth's size and mass, respectively. Solar distance, similar mean density, and cosmochemical models for solar system evolution led to the inference that Venus and Earth share similar bulk composition and heat-producing elements (Wetherill, 1990). Soviet Venera and Vega landers indicate surface element abundance consistent with basaltic composition (e.g., Surkov, 1986), although the limited data could accommodate other compositions. Geomorphic and geochemical arguments also support a basalt interpretation (Bridges, 1995, 1997; Grimm and Hess, 1997). Slow retrograde motion makes a Venus day (243 Earth days) longer than its year (~225 Earth days), a factor that may contribute to Venus's lack of a magnetic field (Yoder, 1997). Venus's atmospheric composition (96% CO_2, 3.5% N_2, and 0.5% H_2O, H_2SO_4, HCl, and HF), surface pressure (~95 bar), and temperature (~475 °C) vary significantly from Earth.

Venus's surface conditions are intimately related to its atmospheric properties. Its caustic dense atmosphere includes three cloud layers from ~48 to 70 km above the surface; the clouds reflect visible light and block optical observation. The upper atmosphere rotates at a rate of ~300 km/h, circulating in four Earth days. Venus's thick atmosphere results in negligible diurnal temperature variations and an enhanced global greenhouse that makes a terrestrial water cycle impossible. Venus lacks obvious evidence of extensive sedimentary layers clearly deposited by wind or water. Venus currently lacks weathering, erosion, sediment transport, and deposition processes that play dominate roles in shaping Earth's surface. Although Venus is presently ultradry, the past role of water is unknown. Isotopic data are consistent with, but do not require, extensive reservoirs of water ≥1 b.y. ago (Donahue and Russell, 1997; Donahue et al., 1997; Donahue, 1999; Lecuyer et al., 2000; Hunten, 2002). Conditions for retaining such reservoirs are not predicted by current climate models (Bullock and Grinspoon, 1996, 2001; Phillips et al., 2001). The present lack of water renders current Venusian crustal rock orders of magnitude stronger than terrestrial counterparts, even given Venus's elevated surface temperature (Mackwell et al., 1998).

Magellan altimetry data and synthetic aperture radar (SAR) image data (Ford and Pettengill, 1992; Ford et al., 1993) permit first-order characterization of Venus's surface. The lowlands lie at or below mean planetary radius (6051.9 km), composing ~80% of the surface. Lowlands include relatively smooth, low-strain surfaces called plains, or planitiae, and linear zones of concentrated deformation called deformation belts (Banerdt et al., 1997). Highland regions (~10% of the surface) include volcanic rises, crustal plateaus, and the unique feature Ishtar Terra (Hansen et al., 1997). Volcanic rises—large domical regions (~1500–2500 km in diameter and ~1–3 km high) marked by local radial volcanic flows—are widely accepted as contemporary (i.e., currently thermally supported) surface expressions of deep mantle plumes on thick Venusian lithosphere (e.g., Phillips et al., 1981, 1991; McGill, 1994; Phillips and Hansen, 1994; Smrekar et al., 1997; Nimmo and McKenzie, 1998). Crustal plateaus, similar in planform to rises, represent steep-sided plateaus, marked by unique tectonic fabrics (called ribbon-tessera terrain), which rise 0.5–4 km above their surroundings. Scientists generally agree that thickened crust supports the crustal plateaus, as evidenced by small gravity anomalies, low gravity to topography ratios, shallow apparent depths of compensation, and consistent admittance spectra (e.g., Smrekar and Phillips, 1991; Bindschadler et al., 1992a, 1992b; Grimm, 1994a; Bindschadler, 1995; Hansen et al., 1997; Simons et al., 1997), although debate ensues with regard to the mechanism responsible for crustal thickening.

Approximately 500 coronae (generally 60–800 km diameter quasi-circular tectonomagmatic features) occur planet-wide, but concentrate at intermediate elevations (Stofan et al., 1997), called the mesoland (~10% of surface). Coronae occur dominantly as chains spatially associated with chasmata (troughs), but they also form clusters associated with some volcanic rises, and they occur as isolated features in the lowlands (Stofan et al., 1992, 1997, 2001). Although coronae are widely accepted as representative of endogenic diapiric structures (e.g., Stofan et al., 1992, 1997; Squyres et al., 1992; Janes and Squyres, 1993; Phillips and Hansen, 1994; Smrekar and Stofan, 1997; Hansen, 2003), formation by exogenic bolide impact have been proposed for some or all coronae (e.g., Greeley, 1987; Vita-Finzi et al., 2005; Hamilton, 2005; McDaniel and Hansen, 2005).

A wide variety of volcanic landforms, preserved at a range of scales, occur across the surface (Head et al., 1992; Crumpler et al., 1997). Volcanic shields, 1–20 km in diameter, occur in shield fields (<300 km diameter regions) and as "shield terrain" distributed across millions of square kilometers; lava flows (up to hundreds of kilometers long) are commonly associated with volcanoes, coronae, and fractures (Crumpler et al., 1997). Volcanic forms are generally consistent with basaltic compositions (e.g., Bridges, 1995, 1997; Stofan et al., 2000).

Venus displays unique narrow channels that trace across the lowlands for tens or hundreds of kilometers (up to the ~6900 km long Baltis) (Baker et al., 1997). Although all scientists agree that the channels are fluid cut, many questions remain debated: Are channels erosional or constructional? Do they represent thermal or mechanical processes? What was the nature of the fluid? What is the substrate? (e.g., Baker et al., 1992, 1997;

Komatsu et al., 1992; Gregg and Greeley, 1993; Bussey et al., 1995; Williams-Jones et al., 1998; Jones and Pickering, 2003; Lang and Hansen, 2006).

Impact Craters

About 970 impact craters (~1.5–270 km diameter) pepper the surface with a spatial distribution almost indistinguishable from random (Phillips et al., 1992; Schaber et al., 1992; Herrick et al., 1995, 1997; Hauck et al., 1998). The population lacks small craters, and all recognized craters are essentially pristine. The paucity of small craters, due to screening by Venus's thick atmosphere, hampers surface age determination, because small craters typically constitute the largest number of craters (McKinnon et al., 1997). In addition, determination of surface age by crater density requires binning across a range of crater diameters—a technique not possible on Venus. A "datable" surface on Venus must exceed ~2×10^7 km^2 in order to be statistically robust, based on impact crater density alone (Phillips et al., 1992). And even an area this large would require assumptions with regard to surface formation that severely limit the uniqueness of any temporal or history interpretation (Campbell, 1999). Some workers have attempted to date geological units by combining morphologically similar units into large composite regions for crater density dating (e.g., Namiki and Solomon, 1994; Price and Suppe, 1994; Price et al., 1996; Basilevsky and Head, 2002). However, these studies lack statistical validity because the crater numbers are not high enough to uniquely quantify local mean densities or formation history (Campbell, 1999). In addition, these studies require the implicit assumption that similar-appearing units formed at the same time, even if spatially separated. Therefore these analyses assume, rather than provide confirmation of, geologic synchroneity (for further discussion see Hansen, 2000).

The pristine condition of most impact craters also presents a challenge to volcanic and tectonic resurfacing models, as discussed later. Although observations are consistent with the interpretation that local geological processes have not modified craters (Schaber et al., 1992; Strom et al., 1994), the low number of craters and current data resolution prevent confirmation of this hypothesis (Hauck et al., 1998). Furthermore, several studies contribute evidence for impact crater modification, presumably by volcanic processes; the floors of radar-smooth craters are several hundred meters shallower than craters with radar-rough floors (Sharpton, 1994; Wichman, 1999; Herrick and Sharpton, 2000). These data suggest that impact craters with radar-smooth floors have experienced postimpact modification, presumably a result of local burial. And yet, few examples of near-complete flooding of craters have been reported. The crater population robustly indicates, however, that Venus lacks large tracts (>>2×10^7 km^2) of very old or very young surfaces. Furthermore, the low average surface density (global average of ~2 craters/10^6 km^2) implies a global average model surface age (AMSA) of ~750 +350/–400 Ma (McKinnon et al., 1997). But what does this global AMSA value mean with regard to Venus's evolution? To answer this question we first briefly discuss the definition of the AMSA.

Average Model Surface Ages

Impact crater density reflects the age of a planetary surface. A "surface" can represent a specific geologic unit, or a region. A region could consist of a subset of a planet surface, or the entire planet surface. A surface could record a single event with respect to impact crater formation and destruction, or an integrated history. The surface age, as defined by impact crater density, yields an "average model surface age," or AMSA. An AMSA is not an absolute age, nor does it necessarily reflect a unique history. In the case of a global AMSA, the model age is dependent on impactor flux models as well as many other factors, including the geologic history of the surface. As an average age, it represents an integrated geologic history. Although Venus's global AMSA can place limited constraints on possible evolutionary models, it can also be accommodated by a number of possible evolutionary histories and operative processes.

Painting of the Golden Gate Bridge serves as an analogy. The distribution of cracking and peeling (evidence of aging) might be similar if the Golden Gate Bridge was either (1) rebuilt and painted in a single day 50 years ago, (2) sandblasted at some point it its past, and then almost completely repainted in a single day 50 years ago, or (3) painted continually over the past 50 years in small local patches. Each hypothesis could address the first-order crack and peel (crater) distribution, which at some level reflects time, but each hypothesis clearly represents fundamentally different evolutionary histories, and each calls on different processes. In order to determine which history and/or processes occurred, we would need to consider criteria other than the distribution of cracking and peeling and to evaluate each hypothesis in light of these other observations.

McKinnon et al. (1997) determined that Venus records a *global* average model surface age (AMSA) of ~750 +350/–400 Ma, based on total impact craters and impactor flux. Because this value is a *global* AMSA, it represents the average model age of a planet's entire surface. A planet can also preserve distinct AMSA provinces, which together add up to the global AMSA. The size, location, and correlation with other factors, of individual AMSA provinces could provide critical clues to the range of processes that contributed to a planet's surface evolution. Individual AMSA provinces must be statistically robust (a function of both local crater density and total crater population [Phillips, 1993; Hauck et al., 1998; Campbell, 1999]). The minimum area that can be dated statistically on Venus by crater density alone is 2×10^7 km^2, or ~4.5% of the planet surface (Phillips et al., 1992). Based on impact crater density alone, no statistically distinct areas of crater density occur across Venus. Therefore, any subdivision of the global AMSA, and the determination of robust individual AMSA provinces, require geological criteria in addition to statistical data (crater density).

As an example, the average model age (i.e., global AMSA) of a township reflects a town's history; but like a global AMSA, a single average model age of a town could be accommodated by numerous histories. Determination of the demographic implications of an average model age of a township's population would require additional information. (1) How is population distributed within the township (spatial relations); (2) do different average model age provinces exist within the township (distinct AMSA provinces); and if so, (3) what are the average model ages, the relative sizes of age provinces, and locations of age provinces within the township? It would also be useful to know how the individual average model age provinces relate to businesses, schools, parks, shops, etc. The more complete the picture of average age provinces relative to other factors, the more specific the clues for unraveling details of the township's spatial and temporal development. Questions with respect to planet AMSA provinces are similar.

A global AMSA alone can, depending on the age, provide critical information about a planet's surface history. If a global AMSA were either very young or very old, then the number of possible evolutionary histories would be limited; in these cases a global AMSA could impose strict constraints on planet evolution hypotheses. For example, Jupiter's nearest moon, Io, records the youngest recorded global AMSA of any solid-surfaced planet in our solar system. This very young global AMSA reflects an extremely active body, in which operative processes are both recent and capable of complete destruction of impact craters. Io's youthful surface results from global volcanism driven by tidal energy, the result of Io's proximity to Jupiter (Johnson, 2004). (Jupiter's surface also lacks impact craters, but its lack of impact craters is attributable to a surface rheology that disallows crater formation.) In contrast, a very old global AMSA (i.e., an AMSA similar to a planet's age of formation) indicates a relatively inactive planet, lacking processes capable of destroying impact craters formed across its surface. If a planet's global AMSA lies between these two end-member cases, then the number of possible evolutionary histories is vast.

Additional clues to a planet's evolution can be gleaned from the occurrence of distinct AMSA provinces across a planet's surface. For example, the Moon, though globally old, preserves regions marked by (1) very old, and (2) old but relatively younger, AMSA provinces (Wilhelms, 1993). The crater-dense highlands define older-AMSA provinces, whereas the comparatively crater-poor maria represent younger-AMSA provinces; each province provides clues, individually and collectively, for various aspects of the Moon's surface evolution.

Venus's global AMSA is neither particularly young nor particularly old (ca. 400–1150 Ma, or 9%–25% of total planet age); therefore, a vast number of different surface histories, and operative processes, could account for its global AMSA. Because a global AMSA is simply a number, the numerical value of Venus's global AMSA can also have vastly different implications within the context of different hypotheses.

VENUS RESURFACING HYPOTHESES

Several hypotheses emerged in early attempts to address the near-random distribution of ~970 apparently pristine impact craters across the surface of Venus. The hypotheses are broadly divisible into two groups: (1) catastrophic/episodic and (2) equilibrium/evolutionary. Catastrophic/episodic hypotheses propose that a global-scale, temporally punctuated, event or events dominated Venus's evolution, as reflected in the generally uniform impact crater distribution (Schaber et al., 1992; Herrick, 1994; Strom et al., 1994). Equilibrium/evolutionary hypotheses suggest instead that the generally uniform crater distribution results from relatively continuous resurfacing in which volcanism and/or tectonism occur across the planet through time, although the style of volcanism and tectonism might vary spatially and might vary over time at any given locale (e.g., Phillips et al., 1992; Guest and Stofan, 1999). Equilibrium/evolutionary hypotheses could also involve a progression from global steady-state equilibrium resurfacing to global impact crater accumulation as a result of secular changes (e.g., Solomon, 1993; Phillips and Hansen, 1998).

Catastrophic hypotheses include (1) a one-dimensional lithospheric instability hypothesis, which calls for wholesale recycling of the lithosphere (e.g., Parmentier and Hess, 1992; Parmentier et al., 1993; Turcotte, 1993; Turcotte et al., 1999), and (2) volcanic burial of a preserved lithosphere (e.g., Schaber et al., 1992; Steinbach and Yuen, 1992; Strom et al., 1994). These hypotheses assume global synchroneity and therefore predict a single global AMSA marking the time of the last lithospheric catastrophe. The catastrophic volcanic resurfacing hypothesis calls for geologically instantaneous (10–100 m.y.) emplacement of thick (1–3 km) volcanic flows across ~80% of Venus, resulting in complete volcanic burial of preexisting impact craters across Venus's lowland (e.g., Herrick, 1994; Basilevsky and Head, 1996). The global AMSA would represent the time of the emplacement of globally extensive lava flows. The near-global catastrophic flooding hypothesis is further incorporated into a directional view of global surface evolution, called the global stratigraphy hypothesis herein (Basilevsky and Head, 1996, 1998; Basilevsky et al., 1997; Head and Basilevsky, 1998).

The global stratigraphy hypothesis predicts an evolution of Venus that brackets and embraces the near-global catastrophic volcanic resurfacing event. The global stratigraphy hypothesis also calls on early, globally extensive, tessera-terrain deformation (and resulting impact crater destruction by the tectonic deformation that resulted in tessera-terrain formation), followed by local warping and crustal thickening, forming isolated high-standing crustal plateaus and the extensive lowlands; the lowlands later collected thick (1–3 km), catastrophically emplaced (10–100 m. y.) flood lava. Wrinkle ridges (~5–30 km wavelength lineaments that mark <2% contractional strain [Banerdt et al., 1997]) deform the purported thick flood lava that covered the lowlands; the hypothesized unit is called wrinkle ridge plains (or plains with wrinkle ridges, unit *pwr*) (Basilevsky and Head, 1996, 1998, 2002; Head and Basilevsky, 1998). According to the global stratigraphy hypothesis, Venus's lowland surfaces represent unit *pwr*, whereas the highland regions marked by crustal plateaus preserve remnant tessera terrain, which escaped flooding due to elevation. Ribbon-tessera terrain would preserve the only record of Venus's precatastrophic flooding processes.

Evolutionary resurfacing hypotheses employ equilibrium, or steady-state, resurfacing concepts, and may include different modes of impact crater accumulation through time. Phillips (1993) proposed an equilibrium volcanic resurfacing hypothesis, which calls for near-steady-state impact crater formation and burial (destruction) through spatially random volcanic activity across local areas (~10^7 km^2, or less). The resulting equilibrium resurfacing comprises a balance between crater formation and burial integrated across space and time. Although the equilibrium volcanic resurfacing hypothesis is dominantly statistical, it specifies that craters were removed by volcanic burial, and therefore it can be tested by geologic observations. The equilibrium volcanic resurfacing hypothesis does not specifically address tessera-terrain formation or any relationship between impact craters and tessera terrain. The global AMSA value, in this case, would not represent a specific date or event, but instead it would reflect the average time required to resurface the planet.

Solomon (1993) proposed a hybrid two-stage surface history in which early steady-state impact crater formation and destruction resulted from global-scale tectonic deformation driven by extremely high heat flow; cooling led to a change in crustal rheology and subsequent accumulation of impact craters across the surface. In this hypothesis, Venus's surface could not preserve impact craters until it cooled significantly; once cooled, the surface accumulated craters since the time of the global rheological transition. The global AMSA would represent the time since the transition in global surface rheology. Subsequent to the proposal of this hypothesis, new flow laws for ultradry diabase (Mackwell et al., 1998) indicate that Venus's crust is too strong, even at elevated surface temperature (~450 °C), to allow for early viscous relaxation of impact craters as hypothesized. Although this hypothesis seems to have been abandoned in light of the new flow laws, the spirit of the hypothesis might be feasible if ancient Venus was wetter than contemporary Venus, resulting in possible regional or local viscous flow, perhaps enhanced by local thermal anomalies.

The various catastrophic resurfacing models, the global stratigraphy hypothesis, and the equilibrium volcanic resurfacing hypotheses are evaluated further herein following a discussion of observations salient to resurfacing hypotheses.

OBSERVATIONS

In addition to accommodating the global AMSA, any viable resurfacing model for Venus must also address the following observations that have emerged from analysis of Magellan data.

1. Venus's impact crater population includes few partially flooded craters and few faulted (tectonized) craters (Phillips et al., 1992; Schaber et al., 1992; Herrick et al., 1997). That is, most impact craters appear relatively pristine. (Figure 1 of Kreslavsky and Basilevsky, 1998, shows a rare example of a possible buried impact crater, 60 km diameter in this case.) Thus the observations seem to indicate that, for the most part, impact crater destruction on Venus is an all-or-nothing endeavor. Impact craters either (1) are not preserved on the surface, (2) form on the surface, but viscously relax, (3) are completely destroyed by tectonic processes, (4) are completely buried beyond recognition, or (5) are preserved in a pristine state, or modified in a way that preserves clear evidence of their impact character.

2. Impact craters with diameter greater than 100 km have rim-terrain heights of ≤650 m (Herrick and Sharpton, 2000). Therefore complete crater burial would require strata greater than this thickness. Presumably, ancient impact craters would far exceed the ~270 km diameter of Venus's largest impact crater, Mead, and as such, would presumably have higher rim-terrain heights, here taken as 1 km.

3. Numerous studies indicate that extensive lowland regions (tens of millions of square kilometers) are covered by thin layers or flows (tens to 100 m thick) (e.g., Guest et al., 1992; Aubele, 1996; Guest and Stofan, 1999; DeShon et al., 2000; Addington, 2001; Hansen and DeShon, 2002; Stofan et al., 2005), and in particular, large tracts of lowland tessera terrain show thin, rather than thick, blanketing of stratigraphically higher flows (Hansen, 2005, 2007; Lang and Hanson, 2007).

4. Impact craters on tessera terrain clearly postdate tessera-terrain deformation (Gilmore et al., 1997). Although areally most tessera terrain is preserved in crustal plateaus (Ivanov and Head, 1996), tessera terrain also occurs locally in large to small outcrops or kipukas called inliers, in the lowland.

5. Impact craters preserve morphological characteristics that record a temporal sequence of degradation in which crater halos are lost and crater troughs and interiors become progressively filled with radar-smooth material over time (Fig. 1) (Izenberg et al., 1994; Herrick and Sharpton, 2000). These relations suggest that impact craters are divisible into broad relative age groups. Young craters display halos and radar-rough interiors. Old craters lack halos and show radar-smooth interiors.

6. Impact crater density taken together with impact crater morphology (observation 5) allows delineation of three separate AMSA provinces based on impact crater density statistics and impact crater morphology (observation 5), which provides critical geological constraints (Fig. 1) (Phillips and Izenberg, 1995). Phillips and Izenberg (1995) reasoned that if Venus's surface only experienced weathering processes (e.g., Arvidson et al., 1992), then impact crater halos, but not the associated impact craters, would disappear with time. However, if volcanic flows bury a surface, then the impact crater and the associated halo would be lost from view. Therefore old surfaces should have an abundance of impact craters but should be statistically deficient in impact craters with halos; in contrast, young *volcanically resurfaced* regions should be statistically deficient in both impact craters and impact craters with halos. Figure 1 illustrates the spatial distribution of the three AMSA provinces. Low crater density (<1.5 craters/10^6 km^2)

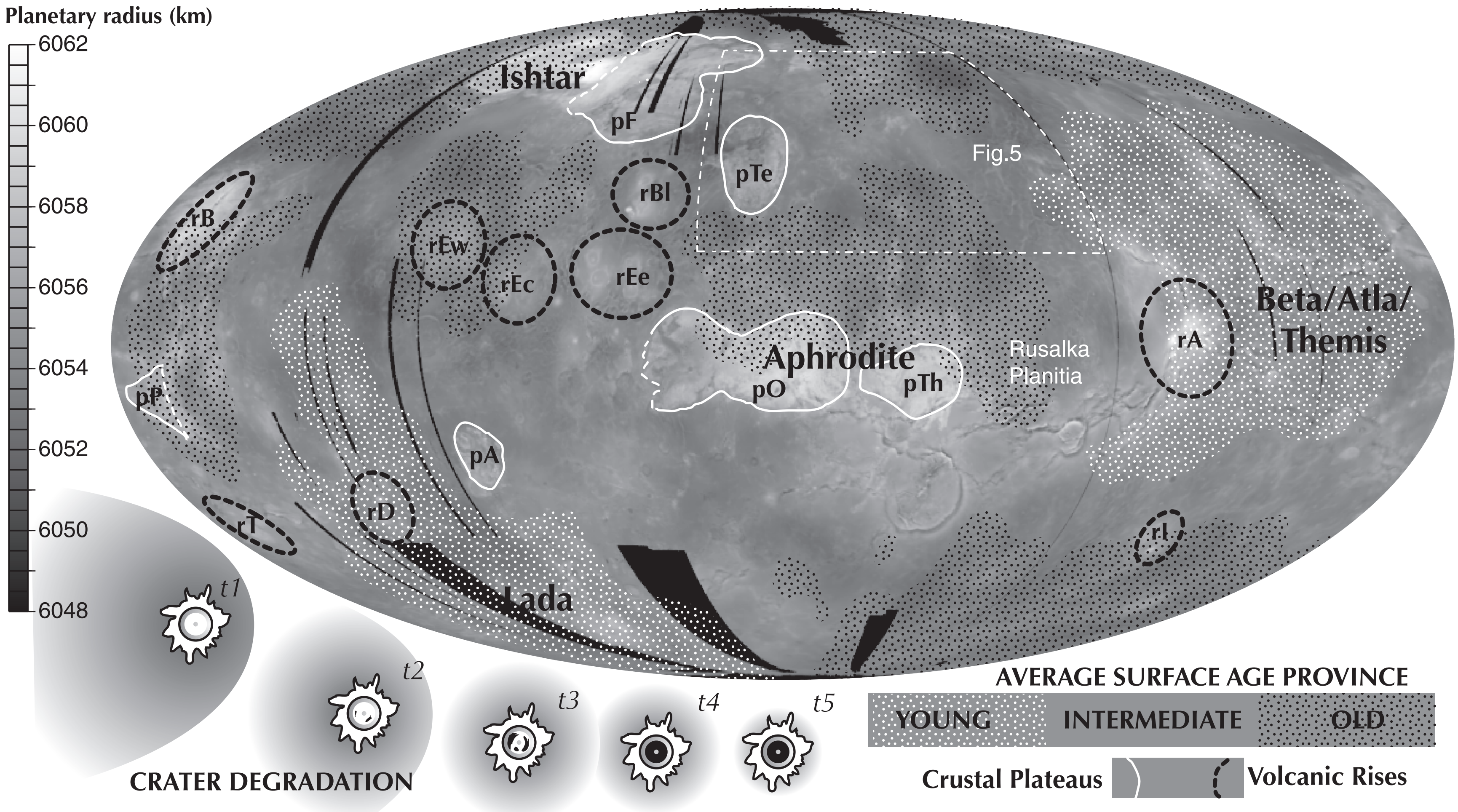


Figure 1. Mollweide projection of Magellan Venus altimetry with average model surface age (AMSA) provinces (data from Phillips and Izenberg, 1995) and major geologic features including crustal plateaus (pA—Alpha; pF—Fortuna; pO—Ovda; pP—Phoebe; pTe—Tellus; pTh—Thetis) and volcanic rises (rA—Atla; rB—Beta; rBl—Bell; rD—Dione; rEc—central Eistla; rEe—eastern Eistla; rEw—western Eistla; rI—Imdr; rT—Themis). Phoebe (pP) is transitional between a plateau and a rise (Grimm, 1994a; Simons et al., 1997; Hansen and Willis, 1998; Phillips and Hansen, 1998). Crater degradation stages illustrated in the cartoon show youngest (t1) to oldest (t5) changes in crater morphology. With time and degradation an impact crater loses its halo, and its interior becomes radar-smooth, presumably as a result of lava fill (Izenberg et al., 1994). AMSA provinces are defined based on impact crater density and impact crater degradation stage. Old-AMSA province has high impact crater density (>2.35 craters/10^6 km^2) and a deficiency in craters with halos. Young-AMSA province has low impact crater density (<1.5 craters/10^6 km^2) and a deficiency in craters with halos. Intermediate-AMSA province has impact crater density between these values and does not have a deficiency in craters with halos (Phillips and Izenberg, 1995) (see text for further discussion). Area of Figure 5 shown with dashed and dotted line.

and a deficiency in craters with halos defines the young-AMSA province; intermediate crater density (2.5–1.5 craters/10^6 km^2) without a halo deficiency defines the intermediate-AMSA province; high crater density (>2.5 craters/10^6 km^2) and a deficiency in impact craters with halos defines the old-AMSA province. Spatial correlation of geologic time-dependent criteria (crater halos) with impact crater density suggests that these AMSA provinces reflect true temporal domains and are not simply the result of stochastic fluctuations in a random distribution (e.g., Campbell, 1999). Building on the work of Phillips and Izenberg (1995), we can compare the three AMSA provinces to major geologic features of Venus (Fig. 1). Salient relationships include

7. Volcanic rises show no preferred spatial correlation with old-, intermediate-, or young-AMSA provinces.

8. Crustal plateaus generally lie in the intermediate-AMSA province, and completely outside the young-AMSA province.

9. Large tracts of the lowlands lie within the old-AMSA province.

10. The Beta-Atla-Themis and southern Lada volcanic provinces, regions of documented tectonic activity and constructional volcanism (Head et al., 1992; Crumpler et al., 1997), lie in the young-AMSA province.

EVALUATION OF RESURFACING HYPOTHESES

Catastrophic Resurfacing and Equilibrium Volcanic Resurfacing Hypotheses

The catastrophic resurfacing and equilibrium volcanic resurfacing hypotheses each accommodate the near-random impact crater distribution, and each accommodates the global AMSA, although with very different implications. Each of these hypotheses has, however, problems addressing some of the observations (1–10).

The lack of obviously embayed impact craters (observation 1) is generally taken to support catastrophic resurfacing hypotheses over the equilibrium volcanic resurfacing hypothesis. The argument is as follows: Broadly synchronous volcanic activity and impact crater formation, across spatially distinct regions through time, as hypothesized following the equilibrium volcanic resurfacing hypothesis, would provide ample opportunity for volcanic embayment and partial burial of impact craters. Thus a lack of significantly embayed or buried impact craters argues against the equilibrium volcanic resurfacing hypothesis.

In addition, given that impact crater rim-terrain heights range up to 650 m (observation 2), the equilibrium volcanic resurfacing hypothesis requires the occurrence of extensive thick stacks (>0.75 km) of globally extensive lava flows stratigraphically above basal tessera terrain to completely bury craters. Although the required thickness could form time-transgressively, the problem is, after more than ten years of analysis of high-resolution SAR images by a number of independent workers reveals growing evidence for the presence of extensive *thin*, rather than thick, lava flows across lowland tessera terrain (observation 3). Catastrophic resurfacing hypotheses also suffer from this observation *if* global catastrophic removal of impact craters is hypothesized to have occurred through burial by globally extensive lava flows (e.g., Steinbach and Yuen, 1992). However, if hypothesized resurfacing resulted from complete lithospheric recycling (e.g., Parmentier and Hess, 1992; Turcotte, 1993; Turcotte et al., 1999), then the relative thickness of lava flows would be inconsequential, and as such, thin flows could be accommodated within the context of these catastrophic resurfacing hypotheses.

Neither the equilibrium volcanic resurfacing hypothesis nor the catastrophic resurfacing hypotheses specifically addresses tessera-terrain versus crater concerns (observation 4); therefore this observation is null with regard to these hypotheses.

The equilibrium volcanic resurfacing hypothesis and the various catastrophic resurfacing hypotheses can accommodate degradation stages of impact craters (observation 5), although none of these hypotheses make specific predictions about the global patterns of degraded craters.

The occurrence of distinct AMSA provinces (observation 6) is incompatible with the various catastrophic resurfacing hypotheses because each predicts that the vast majority of Venus's surface was rapidly cleansed of craters; therefore Venus should record a single global AMSA, with no regional AMSA provinces (Phillips and Izenberg, 1995). In contrast, the occurrence of distinct AMSA provinces is compatible with the equilibrium volcanic resurfacing hypothesis, which calls for near-steady-state crater formation and burial at a global scale. Because the balance is integrated over time, the hypothesis accommodates, and even predicts, the occurrence of spatially distinct AMSA provinces (Phillips and Izenberg, 1995). The equilibrium volcanic resurfacing hypothesis does not, however, address specific correlation of distinct AMSA provinces and geologic features, and therefore observations 7–10 are null to the equilibrium volcanic resurfacing hypothesis.

In summary, the pristine character of most impact craters (observation 1) and documentation of thin rather than thick stacks of lava flows across Venus (observation 3) are incompatible with the equilibrium volcanic resurfacing hypothesis. The occurrence of three distinct AMSA provinces (observation 6) is incompatible with the various catastrophic resurfacing hypotheses, which predict a single global AMSA.

The Global Stratigraphy Hypothesis

Although the global stratigraphy hypothesis includes catastrophic resurfacing, the hypothesized volcanic resurfacing is not global in extent, but instead covers 80% of the planet surface. The global stratigraphy hypothesis also proposes a directional global evolutionary history. Therefore, unlike the other global catastrophic resurfacing hypotheses, the global stratigraphy hypothesis can accommodate distinct AMSA provinces, and it makes specific predictions about the spatial correlation of the distinct AMSA provinces and major geologic features.

We can evaluate the implications of the global stratigraphy hypothesis through the construction of a cartoon sequence (Fig. 2) that tracks salient features of the hypothesized surface evolution with respect to (1) timing of tessera-terrain formation, (2) post-tessera-terrain impact crater formation, (3) uplift of elevated plateaus, and (4) impact crater burial due to catastrophic flooding, as described within the context of the global stratigraphy hypothesis (e.g., Ivanov and Head, 1996; Basilevsky and Head, 1996, 1998, 2002; Basilevsky et al., 1997; Head and Coffin, 1997; Head and Basilevsky, 1998). Initially, impact craters accumulate across an ancient planet surface (t1). Intense global deformation resulted in a global distribution of tessera terrain (parquet pattern, t2). Global-scale tessera-terrain deformation obliterated all preexisting impact craters, and deformation occurred quickly because no impact craters formed during the global-scale tessera terrain–forming deformation event) (Gilmore et al., 1997, 1998). The global stratigraphy hypothesis calls for impact crater destruction by tectonic faulting and folding rather than viscous flow called for by Solomon (1993). Following tessera-terrain formation, Venus's surface, now completely covered by global tessera terrain, began to accumulate impact craters once again (t3). At some point following tessera-terrain formation, crustal plateaus formed, serving to raise local tessera terrain and local craters in elevated plateaus above surrounding tessera terrain that remained in the lowland (t4). In the simple cartoon, black circles indicate regions of crustal plateau formation (Fig. 2).[1]

Following plateau formation, near-global catastrophic volcanic flooding filled the lowlands with extensive thick flood lava to a depth of 1–3 km (t5). The flood lava must have been thick enough to completely cover all lowland impact craters that formed after the hypothesized globally extensive tessera-terrain deformation but before catastrophic resurfacing. (In the global stratigraphy hypothesis, tessera terrain represents the globally extensive preflood surface.) Given the lack of evidence for partially flooded impact craters (observation 1), the global stratigraphy hypothesis requires that all lowland impact craters that had formed after tessera-terrain formation but prior to lowland flooding must be completely buried by flood lava. Therefore, a minimum thickness of ~1 km flows are required (observation 2). Individual flows could be thinner than 1 km, but the hypothesis requires a regionally extensive composite thickness of 1 km emplaced over 10–100 m.y.

According to the global stratigraphy hypothesis, lowland flood-lava flows, once solidified, were deformed by regularly distributed wrinkle ridges, thus forming the unit "wrinkle ridge plains" or plains with wrinkle ridges, *pwr*. Following catastrophic volcanic resurfacing of the lowland, the entire planet surface began to accumulate impact craters once again (t6). Volcanic rises formed late in Venus's history.

The global stratigraphy hypothesis makes specific predictions with regard to the distinct AMSA provinces and geologic terrain. (1) Because impact craters were not buried in elevated crustal plateaus, crustal plateaus should preserve both preflooding (but post-tessera-terrain) impact craters and postflooding impact craters. As such, crustal plateaus should correlate with the oldest-AMSA provinces preserved on the planet. (2) All lowland regions, which are purported to host the hypothesized *pwr* unit, should correlate with younger-AMSA provinces. (3) Volcanic rises should correlate with young-AMSA provinces, given that they formed after flooding. However, as discussed above, spatial relations appear generally opposite to these three predictions (Fig. 1).

Further contradiction of prediction 2 results from a global survey of impact crater density related to geomorphologic units. Price et al. (1996) documented slightly *higher* impact crater density on unit *pwr*, suggesting older surface age of unit *pwr* as compared to tessera terrain. That result is consistent with the relationship between AMSA provinces and crustal plateaus illustrated in Figure 1. The hypothesized *pwr* unit preserves higher impact crater density than tessera terrain, and likely indicates a generally older AMSA for the hypothesized *pwr* unit (or more broadly, lowland surfaces) as compared to tessera terrain preserved in elevated crustal plateaus. Price et al. (1996) suggested that the only way the higher impact crater density could be reconciled with the hypothesized younger age of the *pwr* unit compared to tessera terrain (e.g. Basilevsky and Head, 1996) might be by invoking a lack of small impact craters on tessera terrain, within statistical variance.

In another study, Gilmore et al. (1997) seemed to contradict the results of Price et al. (1996), finding that tessera terrain has slightly higher impact crater density than the hypothesized *pwr* unit. The discrepancy is probably due to Gilmore et al.'s (1997) including both the Beta-Atla-Themis and Lada regions (areas of young AMSA shown in Fig. 1) with the hypothesized volcanic (*pwr)* unit. Thus the *pwr* unit itself would have a higher crater density, if these regions are not considered part of unit *pwr*.

The global stratigraphy hypothesis also faces other challenges. Although it is assumed that unit *pwr* was emplaced in a 10–100 m.y. period, no specific data require (or support) this interpretation. The unit *pwr* is defined on the basis of wrinkle ridges (e.g., Basilevsky and Head, 1996, 1998, 2002; Basilevsky et al., 1997; Head and Coffin, 1997; Head and Basilevsky, 1998). However, wrinkle ridges are secondary structures, and as such, postdate unit emplacement and should not be used to defined a material unit (Wilhelms, 1990; Hansen, 2000). In addition, recent geologic mapping indicates that wrinkle ridges formed at various times across Venus's surface (McGill, 2004). Thus neither wrinkle ridges nor the materials they deform can be used as a robust marker unit or time line in Venus's evolution (see discussion on map unit correlation in Compton, 1985, p. 85–86). Furthermore, the global stratigraphy hypothesis requires (1) complete burial of all early-formed impact craters across the lowland by thick lava flows, and (2) that early-

[1]The global stratigraphy hypothesis embodies an internal contradiction. Hypothesis framers call for *globally synchronous* tessera-terrain formation in order to destroy preexisting impact craters; and they call for crustal plateau formation via the downwelling model (e.g., Bindschadler and Parmentier, 1990; Bindschadler et al., 1992a, 1992b; Bindschadler, 1995). However, the downwelling hypothesis for crustal plateau formation calls for *time-transgressive* tessera-terrain formation above *individual spatially localized* cold mantle downwellings. We disregard this internal contradiction of the global stratigraphy hypothesis herein and evaluate the hypothesis on other grounds. The mode of plateau formation is not of first-order concern here; therefore, within the context of this discussion we simply accept that plateaus formed.

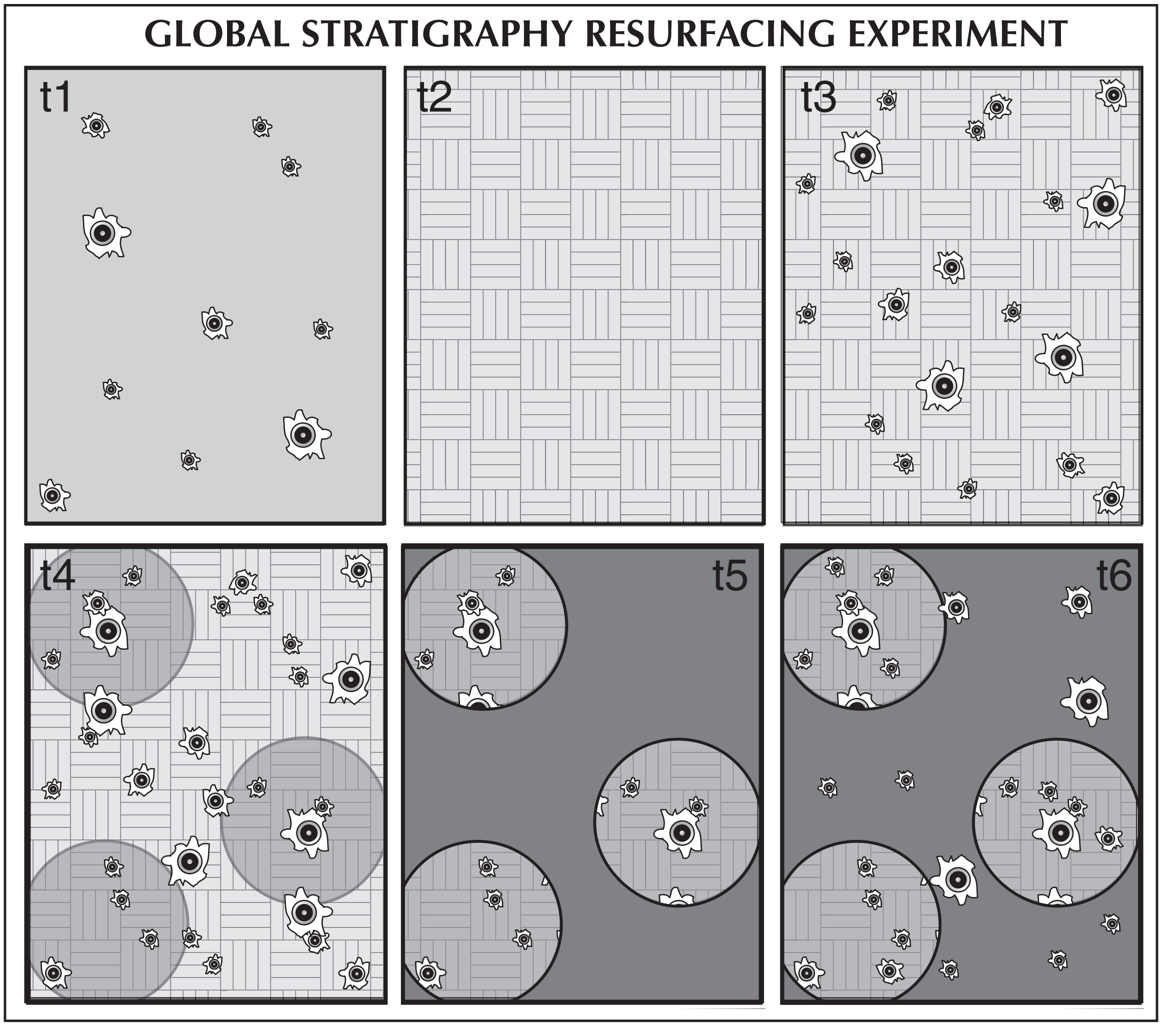


Figure 2. Time-step cartoon constructed to illustrate the hypothesized surface evolution within the context of the global stratigraphy hypothesis. Initially the ancient planet surface accumulates impact craters (t1). Later, globally extensive intense, and temporally punctuated, tectonic deformation results in formation of the purported globally extensive tessera terrain (t2). As a result of tessera-terrain formation, all previously formed impact craters are destroyed (the global and local AMSA would be reset to zero). Following short-lived tessera-terrain formation, the planet surface again accumulates impact craters (t3). Local uplift within quasi-circular regions forms crustal plateaus (t4). Catastrophically emplaced lava flows (unit *pwr*) flood the lowlands with 1–3 km thick lava, burying all lowland impact craters and preserving impact craters (and earlier-formed tessera terrain) within the topographically elevated crustal plateaus (t5). The planet surface begins to accumulate impact craters again following the emplacement of lowland flood lava (t6). See text for further discussion.

formed impact craters were destroyed by tessera-terrain deformation. However, geologic mapping reveals evidence for thin, not thick, lava flows across large parts of the lowland including tessera terrain—regions hypothesized as preflood surfaces in the context of the global stratigraphy hypothesis (observation 3). Furthermore, the relatively organized strain recorded by ribbon-tessera terrain makes it difficult to justify impact crater destruction by tectonic deformation (e.g., Hansen and Willis, 1996; Pritchard et al., 1997; Ghent and Hansen, 1999).

It would also seem that if the impact craters that formed after tessera-terrain formation but prior to flooding were completely buried by thick lava flows, then strain partitioning resulting from subsequent deformation (responsible for the formation of wrinkle ridges and regional fractures) should reveal clues of the buried impact craters. Mechanical anisotropy commonly results in partitioning of strain fabrics. Therefore the continuity of structural fabrics could reflect the anisotropic or isotropic character of a material relative to the scale of strain. Given that impact craters range from 1.5 to 270 km in diameter (with presumably even larger impact features formed in the past) with rim heights up to 1 km (Herrick and Sharpton, 2000), such features could be expected to represent anisotropic features if buried in 1 km thick lava flows. Examination of the surface across Venus indicates incredible regional continuity of wrinkle ridges (generally spaced 5–30 km) and extensional fractures (spaced from 2 to >10 km) across huge expanses of the lowlands (e.g., Banerdt and Sammis, 1992; McGill, 1993; Banerdt et al., 1997; Sandwell et al., 1997; Bilotti and Suppe, 1999). These observations are difficult to justify if the lowlands harbor buried impact craters.

TOWARD DEVELOPING AN ALTERNATIVE WORKING HYPOTHESIS

None of the previously proposed resurfacing hypotheses addresses all of the observations (1–10). These observations serve as model constraints but also provide clues to the formulation of viable resurfacing hypotheses. Venus resurfacing models fundamentally address impact crater formation and removal. Assuming that impact craters can form over most (if not all) of Venus's history, we focus here on mechanisms for impact crater destruction. Given that partially preserved craters are extremely rare (observation 1), crater removal processes apparently completely obliterated or covered preexisting craters. Global-scale crater obliteration through wholesale lithosphere recycling cannot accommodate observations 6–10, and complete crater burial by thick stacks of volcanic flows (whether at global, near-global, or local scales) is contrary to results of geologic mapping (observation 3). However, these constraints can all be accommodated if localized endogenic mantle-lithosphere processes, or localized exogenic processes, destroyed craters over large localized regions, but not the entire surface at once. Such a model might be able to incorporate aspects of the various hypotheses into a viable equilibrium/evolutionary model of Venus's resurfacing consistent with the observational constraints.

Crustal plateaus, which dominantly lie within intermediate-AMSA provinces (Fig. 1), might offer critical clues. Seven crustal plateaus, from north to south, occur on Venus: Fortuna, Tellus, western Ovda, eastern Ovda, Thetis, Phoebe, and Alpha (Fig. 1). (Phoebe differs from other crustal plateaus and perhaps should not be considered in the same light. Phoebe's geophysical characteristics are hybrid between plateaus and volcanic rises [Grimm, 1994a; Simons et al., 1997; Kiefer and Peterson, 2003], and Phoebe's structural fabrics are unique on Venus [Hansen and Willis, 1996].) Crustal plateaus host distinctive deformation fabrics called ribbon-tessera terrain (Hansen and Willis, 1998). Arcuate inliers of characteristic ribbon-tessera terrain also outcrop across expanses of Venus's lowland (Ivanov and Head, 1996; Ghent and Tibuleac, 2002). These tessera-terrain inliers are widely accepted as remnants of ancient crustal plateaus (Bindschadler et al., 1992b; Phillips and Hansen, 1994; Bindschadler, 1995; Ivanov and Head, 1996; Hansen and Willis, 1998; Nunes et al., 2004). As noted, scientists generally agree that thickened crust supports crustal plateaus, but they disagree with regard to the mechanism responsible for crustal thickening. Three divergent models for crustal plateau formation have been proposed: the downwelling, plume, and lava pond–impact hypotheses.

Although the debate of crustal plateau formation is perhaps one of the most hotly debated topics to emerge from the NASA Magellan mission, the common elements, rather than the divergent elements, of each hypothesis might be most important to the resurfacing discussion here. The downwelling hypothesis involves thickening by subsolidus flow and horizontal lithospheric accretion of ancient thin lithosphere associated with a focused cold mantle downwelling (Bindschadler and Parmentier, 1990; Bindschadler et al., 1992a, 1992b; Bindschadler, 1995). The plume hypothesis accommodates thickening via magmatic underplating and vertical accretion due to interaction of ancient thin lithosphere with a large thermal mantle plume (Hansen et al., 1997; Phillips and Hansen, 1998; Hansen and Willis, 1998; Hansen et al., 1999, 2000). The lava pond–impact hypothesis calls for plateau formation through crystallization and progressive deformation of a huge lava pond, the result of massive melting of the mantle due to large bolide impact with ancient thin lithosphere (Hansen, 2006). (For a discussion of the downwelling/plume debate, see Hansen et al. [1999, 2000], Gilmore et al. [1998], and Gilmore and Head [2000]. Hansen [2006] recently proposed the lava pond–impact hypothesis.)

Four critical points of agreement across these three divergent hypotheses are pertinent to the current discussion. (1) Preexisting impact craters would be completely destroyed across the area of individual plateaus (2–5 × 10^6 km^2) as a result of the hypothesized mechanism of plateau formation. (2) Individual plateaus formed temporally and spatially distinct from one another. (3) Plateaus formed on globally thin lithosphere, a condition presumed by many workers to exist during Venus's ancient past (Solomon, 1993; Grimm, 1994b; Solomatov and Moresi, 1996; Schubert et al., 1997; Hansen and Willis, 1998; Phillips and Hansen, 1998; Brown and Grimm, 1999). (4) Large arcuate ribbon-tessera terrain, variably preserved within the lowlands, represent remnants of ancient crustal plateaus. Points 1–4 mean that, independent of the favored mechanism, workers agree that plateau formation resulted in complete crater destruction across large, but localized, areas (2–5 × 10^6 km^2) time-transgressively during "early" Venus history.

Figure 3 presents a cartoon sequence that highlights the salient features of the surface evolution with regard to impact crater formation and destruction resulting from crustal plateau formation by any of the three hypothesized mechanisms. The sequence begins with a surface decorated with preexisting impact craters (t1). As a result of the formation of an individual crustal plateau (whether by downwelling, plume, or lava pond), impact craters are obliterated in the immediate area of the crustal plateau (t2), and the region takes on the characteristic deformation fabric (ribbon-tessera terrain) of crustal plateaus (t3). The specific mode of crater destruction and mode of tessera-fabric evolution depends on the favored mode of crustal plateau formation, but these details are not critical for the current discussion.

In the case of crater destruction by downwelling, obliteration would involve tectonic deformation. In the plume hypothesis, obliteration is due to thermally induced viscous relaxation

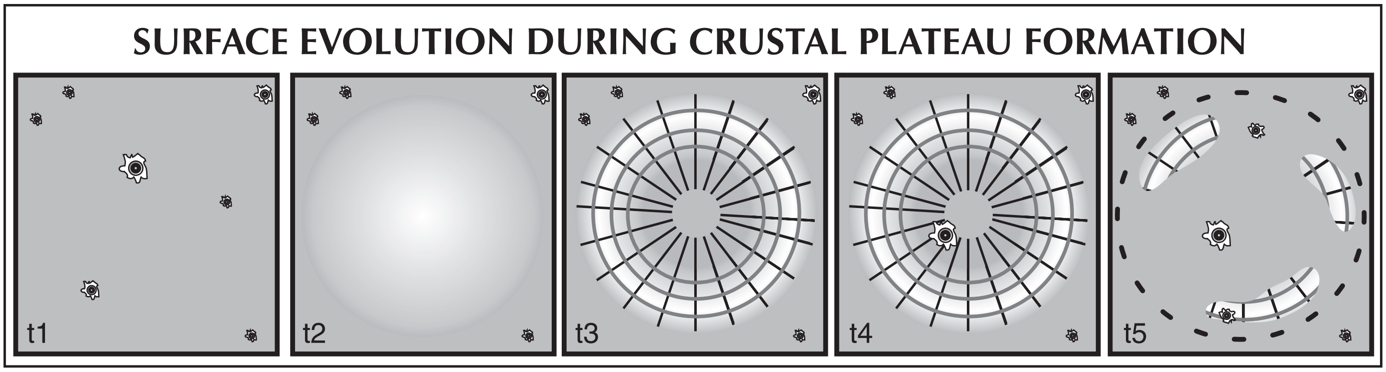


Figure 3. Time-step cartoon illustrating the evolution of the surface following the three hypotheses of crustal plateau formation. The sequence begins with a surface decorated with preexisting impact craters (t1). Formation of an individual crustal plateau (whether by downwelling, plume, or lava pond) obliterates any impact craters in the area of the crustal plateau (t2), and the region takes on the characteristic deformation fabric (ribbon-tessera terrain) of crustal plateaus (t3). Local AMSA at the plateau is reset to zero at this time. Ribbon-tessera-terrain structures form in the area of the crustal plateau (t3). As the plateau stabilizes, new impact craters can form on its surface (t4), and local AMSA increases. With time, regional long-wavelength plateau topography can decay, yet short-wavelength tectonic structural topography associated with tessera-terrain fabric survives (Nunes et al., 2004). Local embayment by thin volcanic material masks local tessera-terrain fabrics (t5). The dashed line marks the limit of the ancient plateau.

of the crust due to plume-lithosphere interactions, and crater destruction would precede development of the tessera fabric, which develops with further plume-lithosphere interaction (for discussion see Hansen et al., 2000). Similarly, the lava pond model hypothesizes that crater destruction immediately predates tessera-fabric formation, although craters are destroyed as a result of bolide impact, massive melting of the mantle, and formation of a huge lava pond that encompasses the area of the crust forming the crustal plateau; tessera-fabric development results from crystallization and progressive deformation of the lava pond scum.

The local AMSA of the plateau region would be reset to zero at time t3 (Fig. 3). The area of an individual plateau is four to ten times too small to date individually with crater density, but the formation of a crustal plateau would lead to a reduction in the local AMSA. As the plateau stabilizes, new impact craters can form on its surface (t4 in Fig. 3). With time, the delicate structural tessera-terrain fabrics can become locally partially buried by flows. Although the flows would be too thin to bury any impact craters formed on tessera-terrain surface, flows could locally bury the delicate tessera fabric, the region surrounding crater ejecta (including flowing into and under porous ejecta), and crater interiors (e.g., Herrick and Sharpton, 2000; Hansen, 2000, 2005). Once formed, crustal plateaus might be susceptible to topographic collapse during thin-lithosphere time, as lower crustal flow leads to long-wavelength topographic decay of a plateau (Nunes et al., 2004). Despite possible loss of long-wavelength topographic expression, distinctive short-wavelength ribbon-tessera-terrain fabrics would survive, providing a record, however patchy, of the former plateau. Any impact craters that had formed on the plateau surface would also survive long-wavelength collapse. Unlike the tessera fabric, however, impact craters display too much local relief to be buried by these flows.

In terms of impact crater population, the surface area involved in crustal plateau formation would be reset to AMSA = 0 during the formation of an individual plateau. Because the areal extent of individual crustal plateaus (~2–5 × 10^6 km^2) is below the maximum (statistical) resurfacing area required by the crater population for equilibrium resurfacing (~10 × 10^6 km^2; Phillips, 1993), crustal plateau formation should contribute to a younging of the local AMSA. However, the plateau region would not be detectable as a distinct surface age province because the areal extent of an individual plateau is significantly below the minimum "datable" area (2 × 10^7 km^2) based on impact crater density alone (Phillips et al., 1992; Phillips, 1993; Hauck et al., 1998; Campbell, 1999).

An Alternative Resurfacing Hypothesis: SPITTER—Spatially Isolated Time-Transgressive Equilibrium Resurfacing

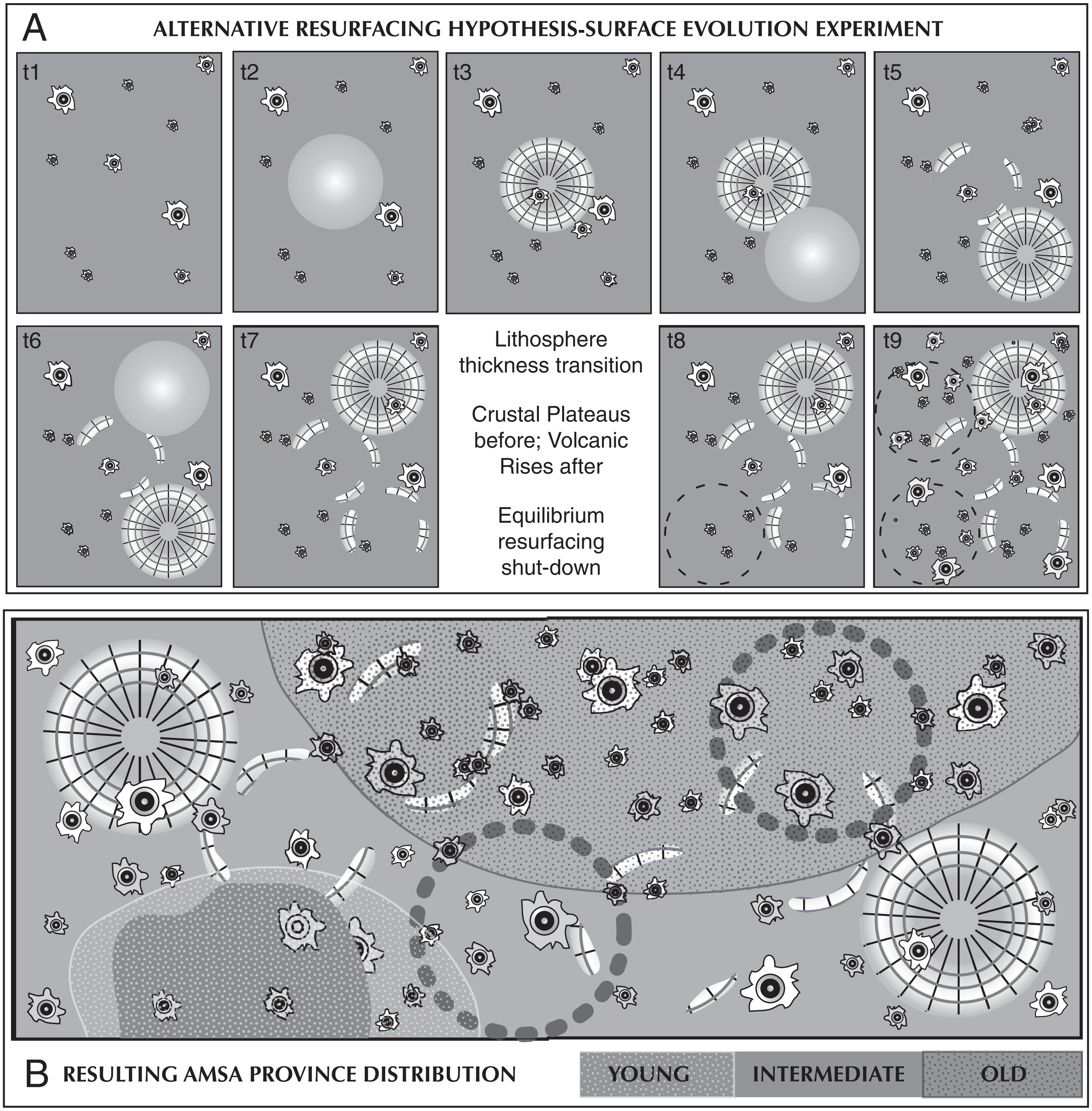
We propose that crustal plateau formation coupled with a global transition from thin to thick lithosphere (e.g., Solomon, 1993; Grimm, 1994b; Solomatov and Moresi, 1996; Schubert et al., 1997; Hansen and Willis, 1998; Phillips and Hansen, 1998; Brown and Grimm, 1999) might provide a viable explanation for impact crater constraints on Venus's resurfacing. During an ancient thin-lithosphere phase, impact crater formation and subsequent removal by localized crustal plateau formation could result in a near-steady-state impact crater distribution across Venus. As Venus transitioned to a thick-lithosphere state, by a combination of conductive cooling and downward thermal accretion, the entire surface would accumulate new craters due to the increased strength of the lithosphere. Notable exceptions to this new phase of crater retention would be local regions of pronounced volcanotectonic activity, such as the Beta-Atla-Themis and Lada regions (Phillips and Izenberg, 1995), where craters might be destroyed by volcanotectonic burial.

Figure 4 illustrates the evolution of Venus's surface and impact crater population following the SPITTER hypothesis. The proposed evolution begins, as with the global stratigraphy hypothesis, with a surface that accumulates impact craters (t1), but subsequent evolution differs. During t2 an individual crustal plateau forms by whatever mechanism (local downwelling, mantle plume, or lava pond generated by a large bolide impact). This event completely destroys the local impact craters across the region that evolves into the crustal plateau. Impact craters outside the aureole of the downwelling, plume, or lava pond would remain pristine. The crustal plateau shows distinctive deformation fabric across the region in which preexisting local impact crater were obliterated (t3). As the crustal plateau stabilizes, it preserves newly formed impact craters upon its deformed surface (t3). Later a new downwelling/plume/bolide interacts with another part of the surface, obliterating any previously formed impact craters within its aureole (t4); this region evolves into a new crustal plateau (t5). Over time, new downwellings/plumes/bolides interact with local lithosphere across the planet surface, destroying impact craters within each of their aureoles (t6, t7). The local AMSA within the area of a newly formed plateau is reduced as a result of plateau formation. At the global scale, the surface could develop a near-equilibrium steady state, marked by a time-averaged balance of global impact crater formation and local impact crater destruction (t2–t7). Local differences in impact crater density could occur, depending in part on the distribution of downwellings/plumes/large bolides on the surface through time. This process could continue as long as the global lithosphere remains thin.

Thickening of the lithosphere would cause a marked change in surface evolution. The interaction of thick lithosphere with a focused cold mantle downwelling, a mantle thermal plume, or a large bolide would not result in plateau formation. Once the global lithosphere reached a critical thickness, localized focused mantle downwelling would not show surface effects, and its occurrence would go completely unrecorded at the surface in terms of impact crater destruction. Similarly, mantle plumes would lack the thermal energy to conduct through a thick lithosphere and impose a noticeable rheological imprint on the surface; a thermal plume might cause regional uplift, and possible localized volcanic activity, as in the case of volcanic rises, but it would not be able to cause destruction of preexisting craters. The collision of a large bolide with a thick lithosphere would cause very little melt to form, and it would certainly not result in massive melting of the crust or mantle (e.g., Ivanov and Melosh, 2003), as would be required for the formation of a huge lava pond. A large bolide would simply make a large crater such as the 270 km diameter Mead Crater. Thus in any of these cases, preexisting impact craters would remain unaffected once the lithosphere thickened to some nominal value. The specific value might depend on the favored mechanism(s) of crustal plateau formation. In any case, destruction of impact craters across large localized areas would cease.

The interaction of large thermal mantle plumes with thick lithosphere could result in the formation of volcanic rises rather than crustal plateaus (e.g., Hansen et al., 1997; Phillips and Hansen, 1998). As a result, the surface would be topographically elevated but there would be insufficient thermal energy to affect the surface rheology leading to crater destruction, or even modification. The formation of a volcanic rise is pertinent to the discussion of AMSA provinces, however. Because volcanic rise formation might involve simply uplifting the existing surface, the AMSA at a volcanic rise should actually be older than the age of the volcanic rise itself, unless a massive outpouring of lava accompanied volcanic rise formation and completely buried impact craters on its flanks. In this case, the volcanic rise might correlate with a young surface age. This means that with a transition from thin to thick global lithosphere, the surface over a global scale would likewise evolve from a quasi-equilibrium reworked global surface (a near-steady-state balance between global impact crater formation and impact crater destruction across large local regions) to a global surface of net impact crater accumulation.

The cartoon in Figure 4B illustrates the predicted correspondence of the three documented AMSA provinces with respect to the major geologic features according to the SPITTER hypothesis proposed here. Old-AMSA provinces should represent either areas completely lacking in ribbon-tessera terrain or areas in which ancient crustal plateaus are severely topographically decayed and ribbon-tessera terrain is variably covered by thin lava flows (assuming more lava coverage with time). Surface areas that were completely unaffected by crustal plateau–forming events (downwellings/plumes/bolides), or affected by early crustal plateau–forming events, could have accumulated impact craters for a significantly longer time than regions affected by more recent crustal plateau–forming events. Plateaus that formed just prior to the switch to globally thick lithosphere might sit high, having been captured (frozen in time) with the transition from thin to thick lithosphere, as originally suggested in the context of the plume hypothesis of crustal plateau formation. These elevated plateaus should preserve relatively younger AMSA than regions affected by ancient crustal plateau formation as recorded by ribbon-tessera-terrain inliers. Volcanic rises could be associated with any AMSA age because rise formation simply lifts a preexisting surface and retains the crater record/history that came before. An individual rise could have formed anytime after the AMSA recorded on its surface. This is conceptually similar to placing a lower limit on the formation age of a sedimentary layer by included fossils. Regions marked by very young AMSA must have truly young average surface histories. As noted, the youngest-AMSA provinces represent surfaces marked by recent volcanotectonic activity within the Lada and Beta-Atla-Themis regions.



The SPITTER hypothesis could accommodate a global AMSA of ~750 +350/–400 Ma, and address observations 1–10. The global AMSA could record, broadly, the time of a change from near-steady-state crater formation and destruction (thin lithosphere) to impact crater accumulation (thick lithosphere), whereas the three distinct AMSA provinces emerge as outlined above. The SPITTER hypothesis accounts for complete local crater destruction and for the pristine state of recognized impact craters (observations 1–2), yet it accommodates the occurrence of thin, rather than thick, lava flows consistent with geologic mapping (observation 3). It predicts that impact craters should not record tessera-terrain deformation (observation 4), and it allows for the preservation of various stages of impact crater degradation (observation 5) and for the occurrence of the three distinct AMSA

Figure 4. (A) Time-step cartoons illustrating the evolution of the surface following the SPITTER hypothesis for Venus's resurfacing (t1–t9). Initially the surface accumulates impact craters (t1). As a crustal plateau forms on thin lithosphere, impact craters within the plateau aureole are destroyed (t2), and characteristic ribbon-tessera-terrain fabrics mark the plateau, which can accumulate new impact craters (t3). A new, spatially separate (isolated), crustal plateau forms on thin lithosphere, erasing impact craters within its aureole (t4). As the second plateau evolves and becomes able to preserve newly formed impact craters, the first-formed plateau could topographically decay, but ribbon-tessera fabrics survive, except where buried by local thin volcanic material; impact craters are not buried by volcanic material (t5). As new plateaus form on the thin lithosphere, impact craters are removed locally, and earlier-formed plateaus are variably covered with thin flows (t6–t7). These processes continue until the lithosphere thickens at a global scale. Crustal plateaus that formed just prior to lithosphere thickening are preserved as high-standing crustal plateaus. Crustal plateaus cannot form on thick lithosphere by any of the three hypothesized mechanisms; however, volcanic rises could form above a large thermal mantle diapir (indicated by the dashed circle) (t8). In the case of volcanic rise formation, impact craters are not erased, because the lithosphere is too thick for crater destruction via subsurface processes. Volcanic rise formation raises the local altitude of the surface but does not affect impact crater density, except by local volcanotectonic processes. The entire global surface becomes one of impact crater accumulation (t8, t9) except for local areas of concentrated volcanotectonic activity in which impact craters are buried from surface lava flows, such as the Beta-Atla-Themis and Lada regions. (B) A composite cartoon surface schematically illustrating three AMSA provinces that would emerge from surface evolution described in A. Old-AMSA provinces (black stipple) would include lowland regions in which ancient crustal plateaus formed, by whatever mechanism (marked by tessera-terrain inliers), or in which no crustal plateaus formed. Young-AMSA provinces (white stipple) would include areas affected by recent volcanotectonic activity that buried both impact craters and their halos (e.g., Beta-Atla-Themis and Lada regions). Intermediate-AMSA provinces would include high-standing crustal plateaus and lowland regions with tessera-terrain inliers marking ancient crustal plateaus. Boundaries between AMSA provinces would not be sharp, as illustrated. Note that volcanic rises could correlate with any of the AMSA provinces because volcanic rise formation would only affect local AMSA if rise formation included extensive volcanotectonic burial of impact craters. In general, rise formation simply elevates a preexisting surface, but it does not otherwise affect impact crater density or morphology.

provinces (observation 6). It further predicts the specific relations of these AMSA provinces with major geologic surface features, crustal plateaus, and volcanic rises (observations 7–10).

The SPITTER hypothesis (1) embodies the spirit of the equilibrium volcanic hypothesis (Phillips, 1993), (2) accommodates broad aspects of the equilibrium view that volcanism and tectonism have occurred across Venus through time, though styles and locations have changed (e.g., Guest and Stofan, 1999), (3) incorporates a secular change in resurfacing processes and dynamic processes (e.g., Solomon, 1993; Grimm, 1994b; Solomatov and Moresi, 1996; Hansen and Willis, 1998; Phillips and Hansen, 1998; Brown and Grimm, 1999), and thus (4) could address some aspects of a broadly defined linear geologic history highlighted by the global stratigraphy hypothesis (e.g., Basilevsky and Head, 1996, 1998, 2002).

The SPITTER hypothesis predicts that lowland regions that correlate with old-AMSA provinces might preserve a record of ancient crustal plateaus. Figure 5 illustrates a reconnaissance geologic map over approximately one-eighth of Venus's surface (25°–75°N, 120°–240°E), an extensive lowland region that broadly correlates with old and intermediate AMSA. The map indicates that structural fabrics preserved within tessera inliers might preserve a record of eight ancient collasped crustal plateau features. More mapping is required to identify patterns in ribbon-tessera terrain globally, but the patterns that emerge in the map area are provocative.

CONCLUSIONS

There are many features and processes that occur on Venus that have not been considered in the context of this brief discussion, including deformation belt formation, corona evolution, fracture zones, chasmata, and many styles of volcanic activity. Regardless, it seems that the relations discussed herein call for a careful reanalysis of the hypothesized, yet almost dogmatically accepted, view of the occurrence of near-global catastrophic resurfacing of Venus through the emplacement of massive amounts of lava in a geological instant. Arguments presented herein may provide tantalizing evidence that Venus's surface might preserve a long and rich history of its surface evolution, contrary to widely held views. In order to discover this history, we must carefully and patiently unravel the geologic histories variably recorded in the spectacular Magellan data sets, ever mindful of our assumptions, both stated and unstated. Careful attention to geologic relations, and stated and unstated assumptions, should lead to robust and reproducible geologic histories, and ultimately to an understanding of the processes that contributed to the recorded history—the ultimate goal of geological analysis (e.g., Gilbert, 1886).

The SPITTER hypothesis presented herein, which combines aspects of many of the previously proposed hypotheses, predicts that Venus's surface could preserve relatively long local histories of composite geologic processes. The SPITTER hypothesis makes a number of testable predictions that can be evaluated by Monte Carlo simulations, flooding experiments, analytical and finite-element models, and a host of geologic mapping studies. The results of these studies should provide criteria that allow hypothesis modification, acceptance, or dismissal. Perhaps the major value of the SPITTER hypothesis is that it provides a significantly different, yet geologically reasonable, view of Venus's evolution compared to that of the widely accepted global stratigraphy hypothesis that requires outpouring of massive volumes of flood lava, covering ~80% of the surface in 10–100 m.y., to a depth of 1–3 km. The global stratigraphy hypothesis and embodied near-global catastrophic volcanic resurfacing, although initially compelling, does not stand up to the rigors of detailed geologic mapping and analysis. Currently the only record that we

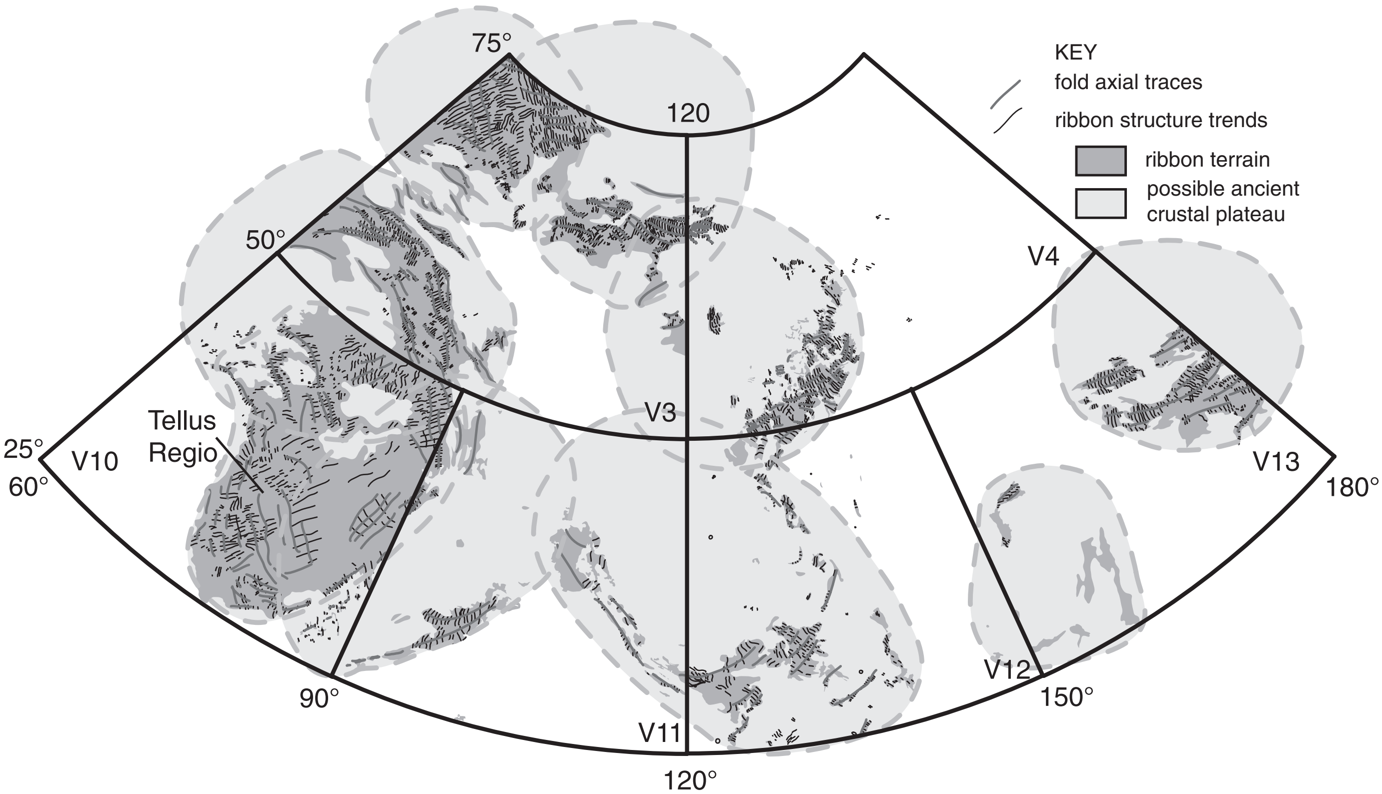


Figure 5. Reconnaissance geologic map of an extensive lowland region (25°–75°N, 120°–240°E). Dark gray regions outline ribbon-tessera terrain; thin black lines parallel ribbon fabric trends; and gray lines mark fold trends. Dashed gray lines and enclosed light gray regions trace eight possible ancient collapsed crustal plateau structures interpreted from ribbon-tessera fabric patterns and crustal plateau Tellus Regio, centered at ~37° N, 140° E.

have of Venus's past is reflected in the surface relations, and as such, these relations provide the strongest constraints that must be addressed by any viable proposals of Venus's resurfacing or related dynamic processes.

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